The Thermochemistry and Hydrodynamics of the Strong Interaction: Results from RHIC

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May 20, 2005

BROOKHAVEN
NATIONAL LABORATORY

RHIC for Chemists

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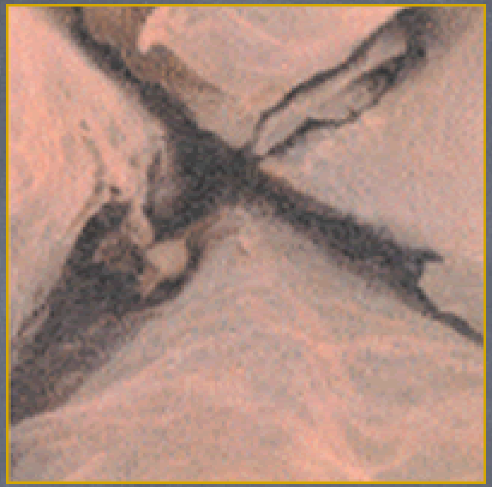
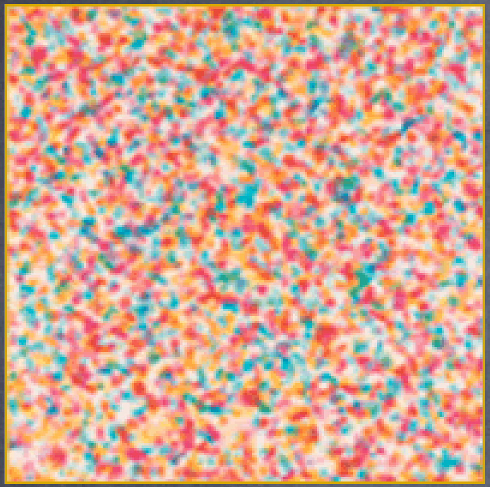
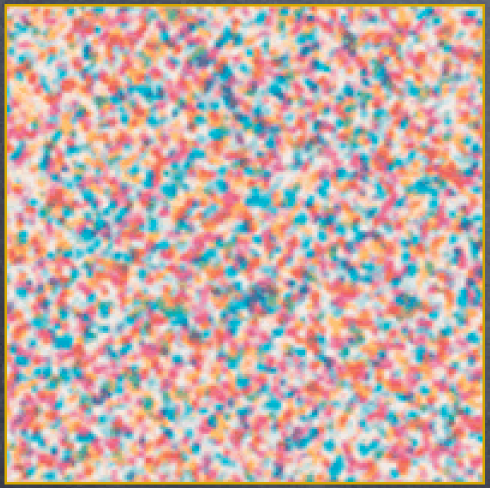
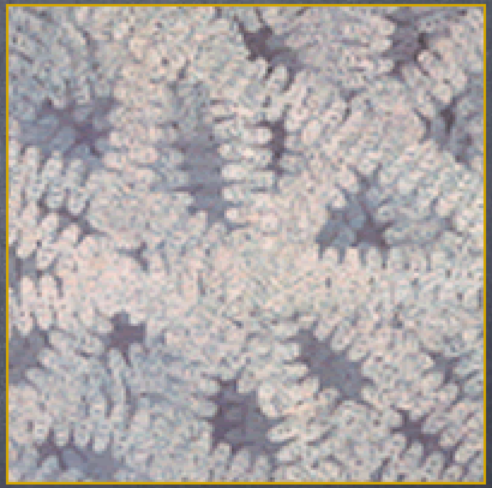
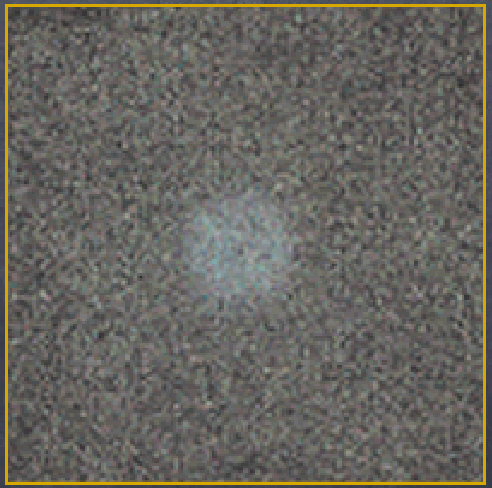
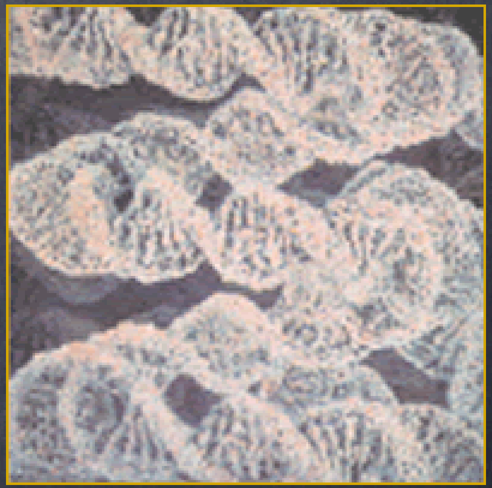





The subject of this talk is nuclear physics, but on subnuclear scales.

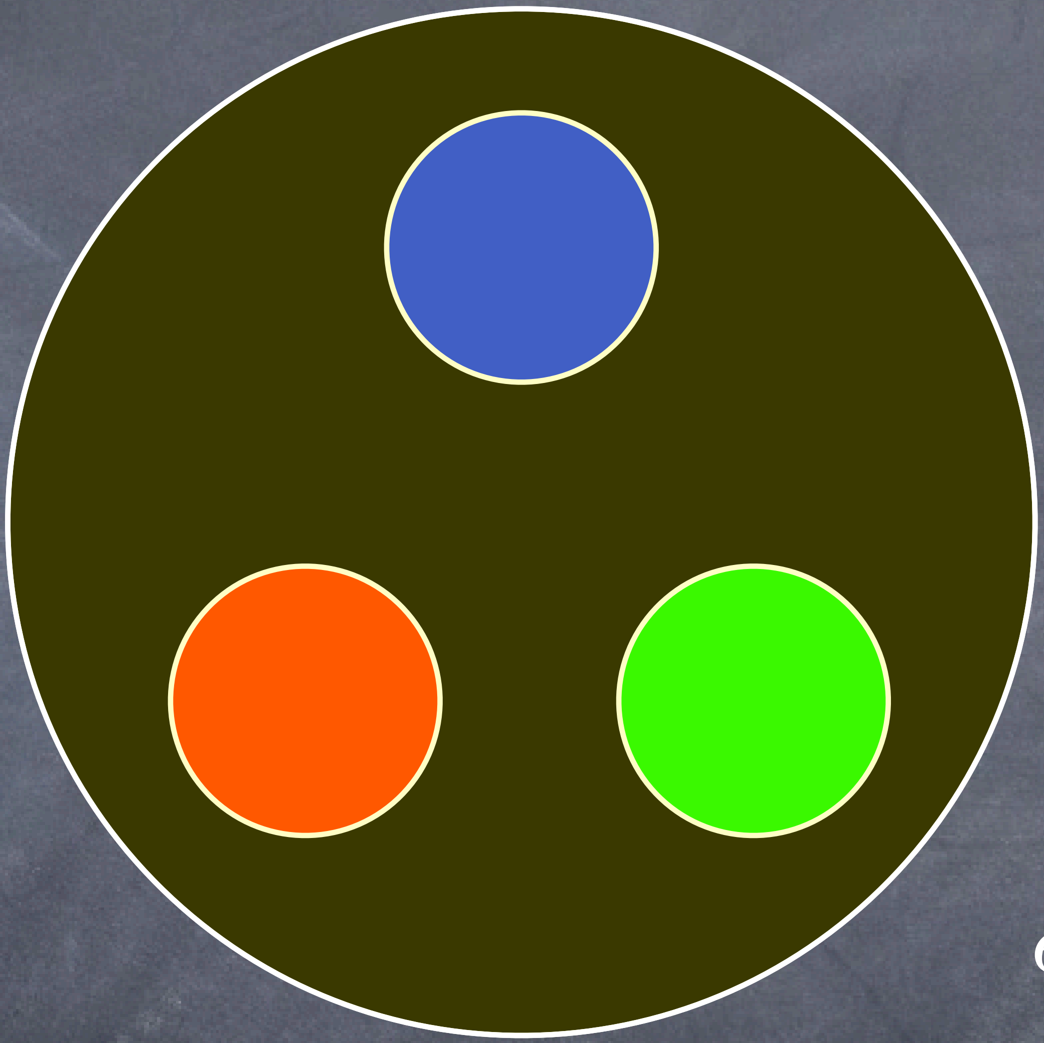





www.powersof10.com

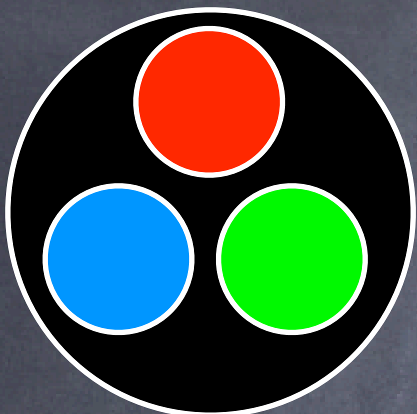
"Inside" a nucleon, we learned that there are 3 quarks that carry its static quantum numbers



$$\epsilon_p \sim 500 \frac{MeV}{fm^3}$$

We also learned that the quarks are constantly interacting via exchange of gluons, the colored photons of Quantum Chromodynamics

QCD Bound States

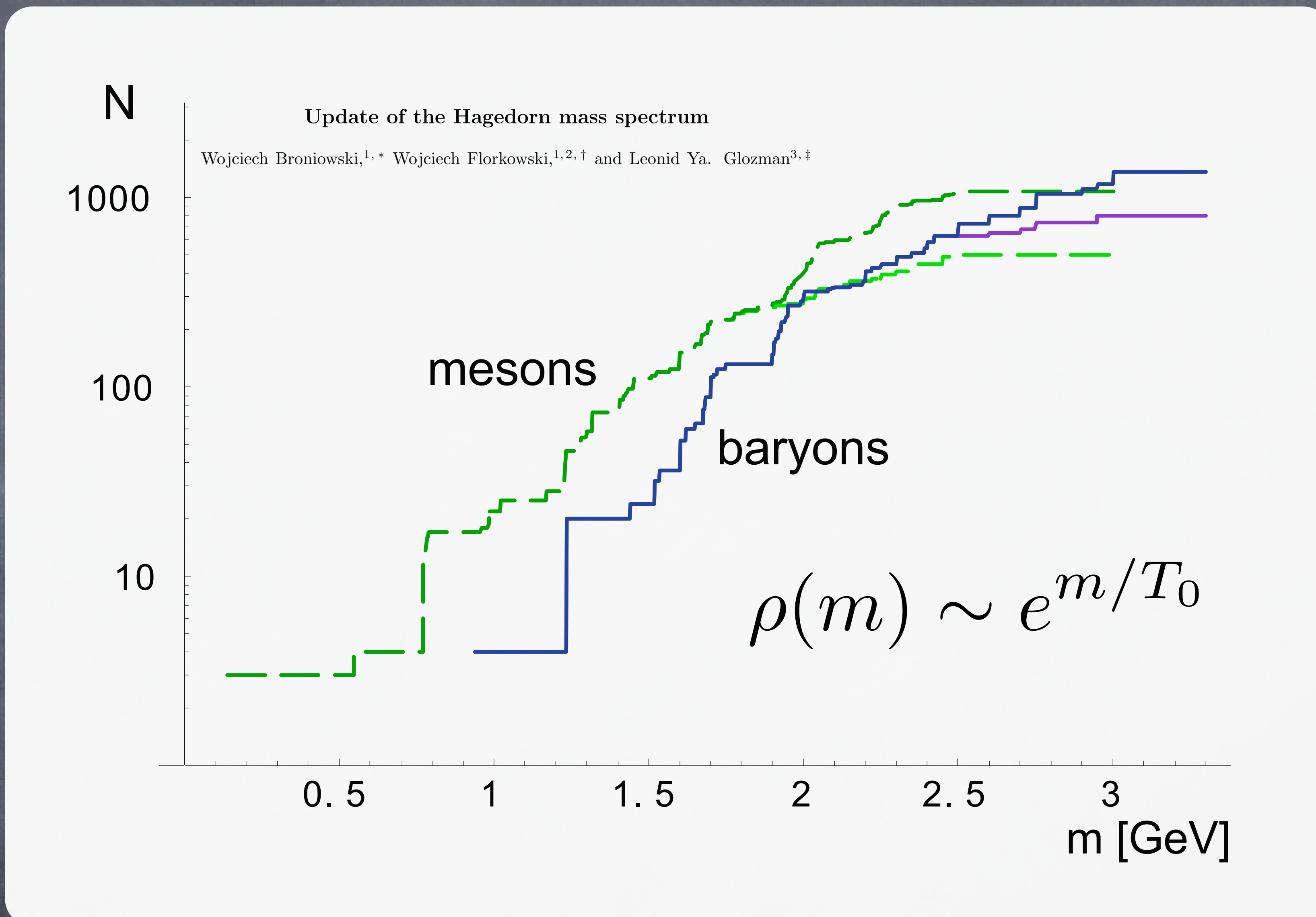


Baryon
(3 q or $\bar{q}$)

Σ Λ Ω p Δ Ξ n

Meson
(1 q & $\bar{q}$)

ω ρ K π φ ρ

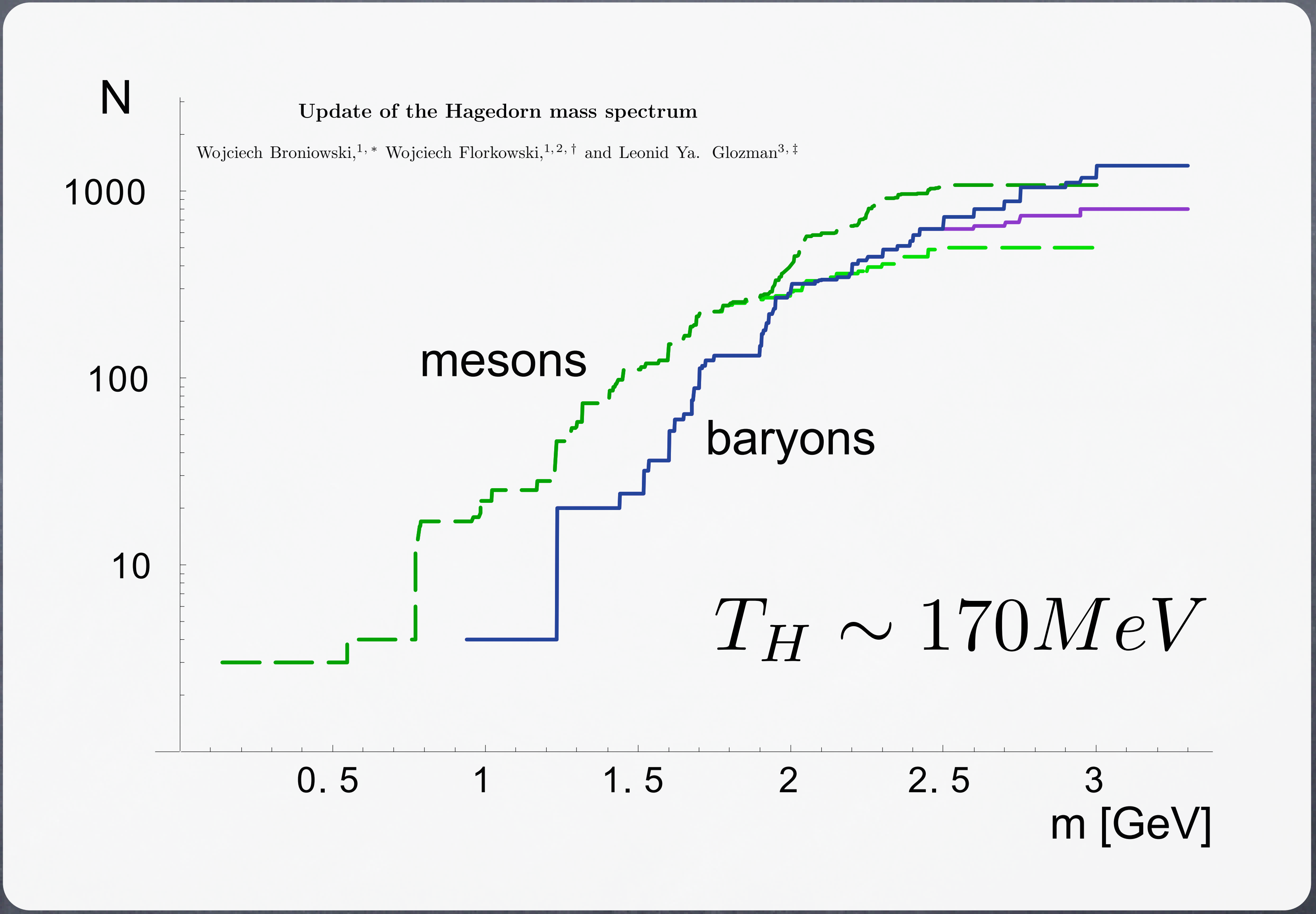


Variety of quarks, angular momentum, parity, etc. gives exponential rise in number of states!

QCD Bound States

R. Hagedorn, CERN (1968)

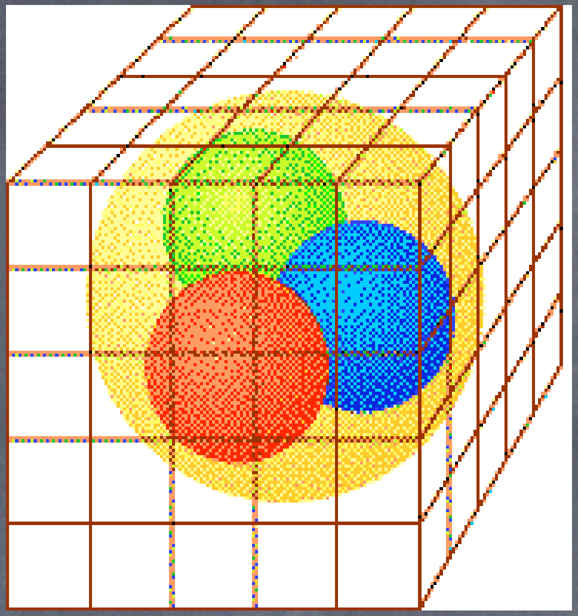
In the early 1960's Rolf Hagedorn predicted that the bound state spectrum would rise indefinitely --> Singularity at limiting temperature T_H



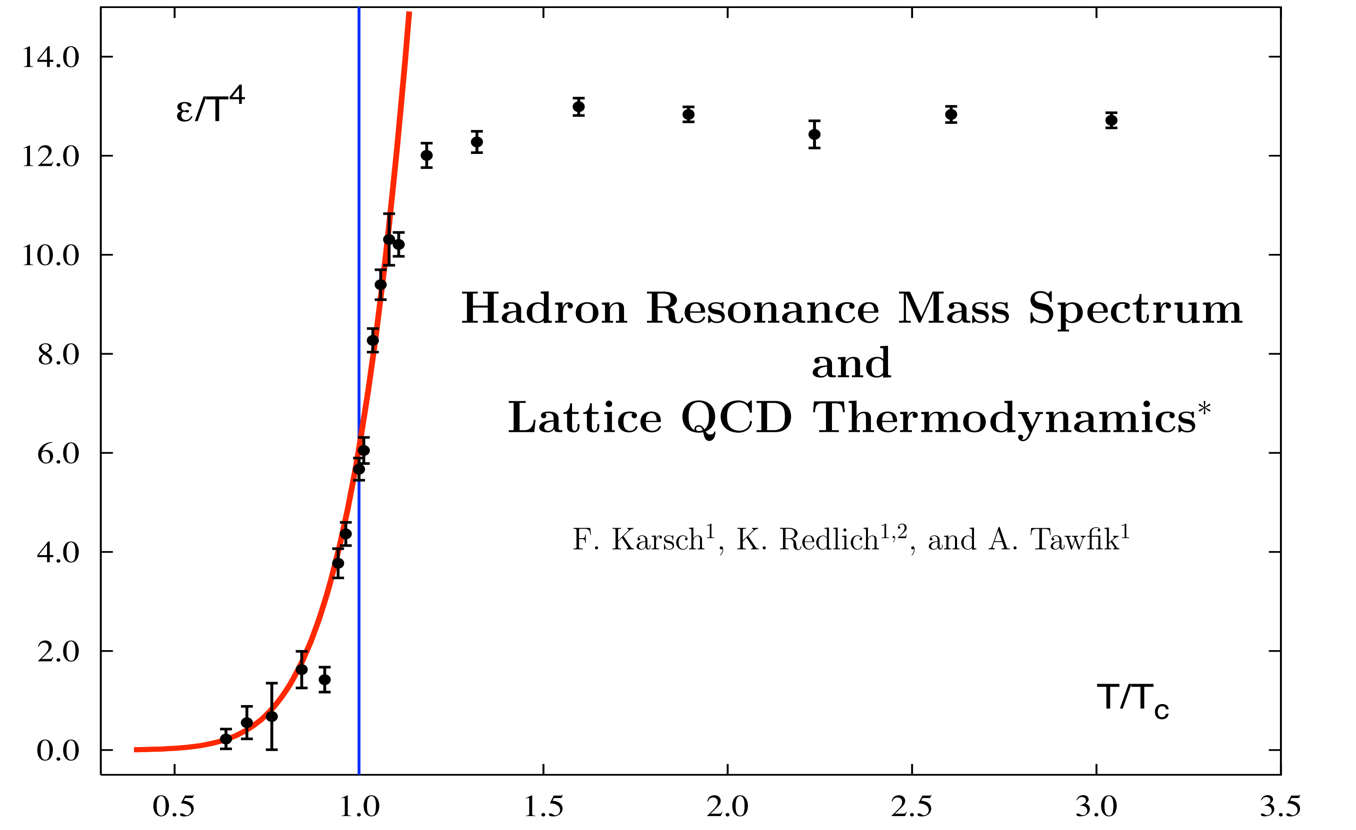
$$\rho(m) \sim m^a e^{m/T_0} \rightarrow Z = \int \rho(m) e^{-m/T} \rightarrow \infty (T \geq T_0)$$

We've come a long way...to 10TFlops
(or 5 Playstation 3's ;-)...)

BNL/RIKEN QCDOC (2005)



Hadron gas joins w/ lattice...



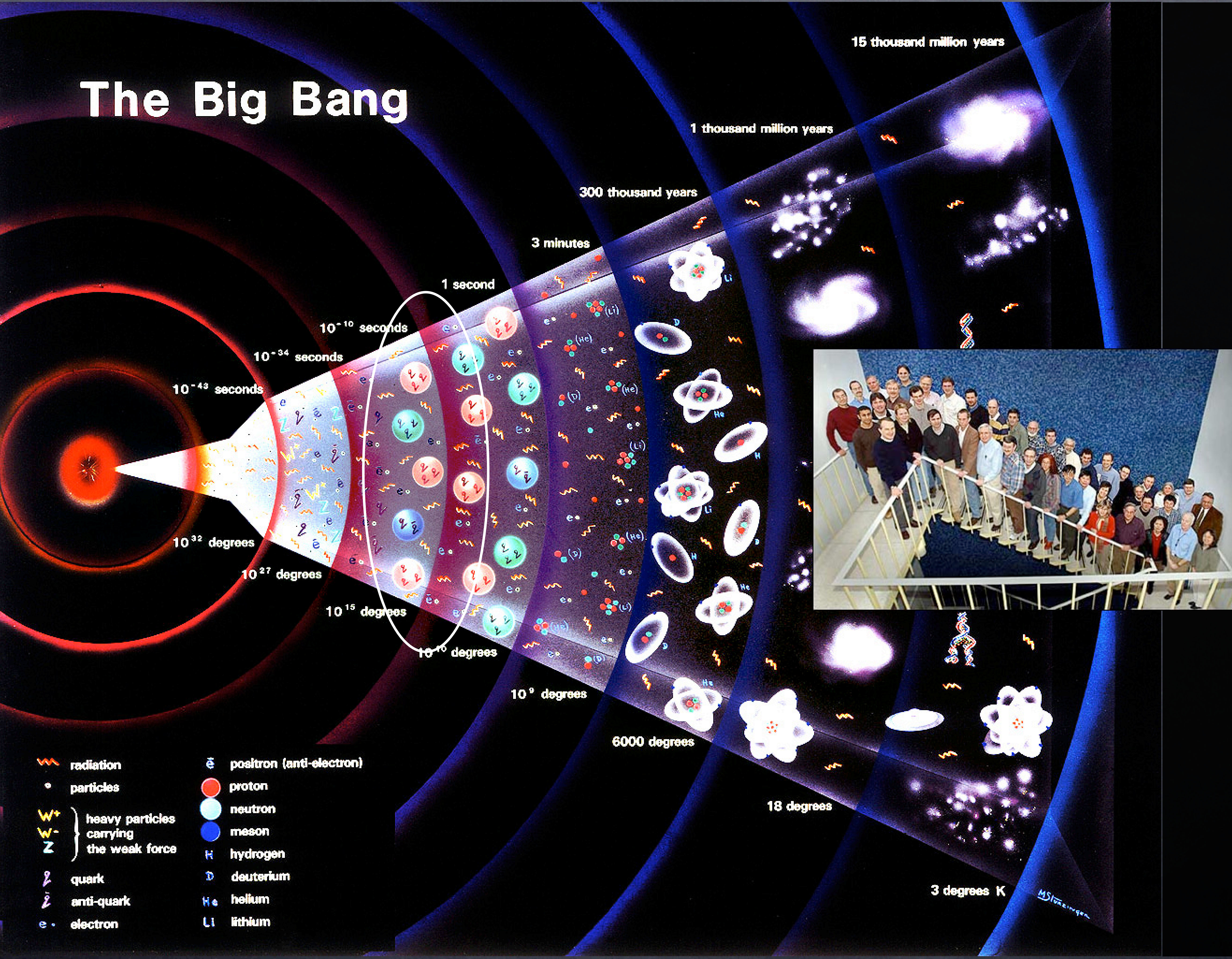
Non-perturbative QCD is notoriously difficult to study analytically

Equilibrium QCD implemented on a lattice shows that there is a phase transition

$$T_c = 173 \pm 15 MeV$$

$$\epsilon_c \sim 700 \frac{MeV}{fm^3}$$

Can we access this experimentally?

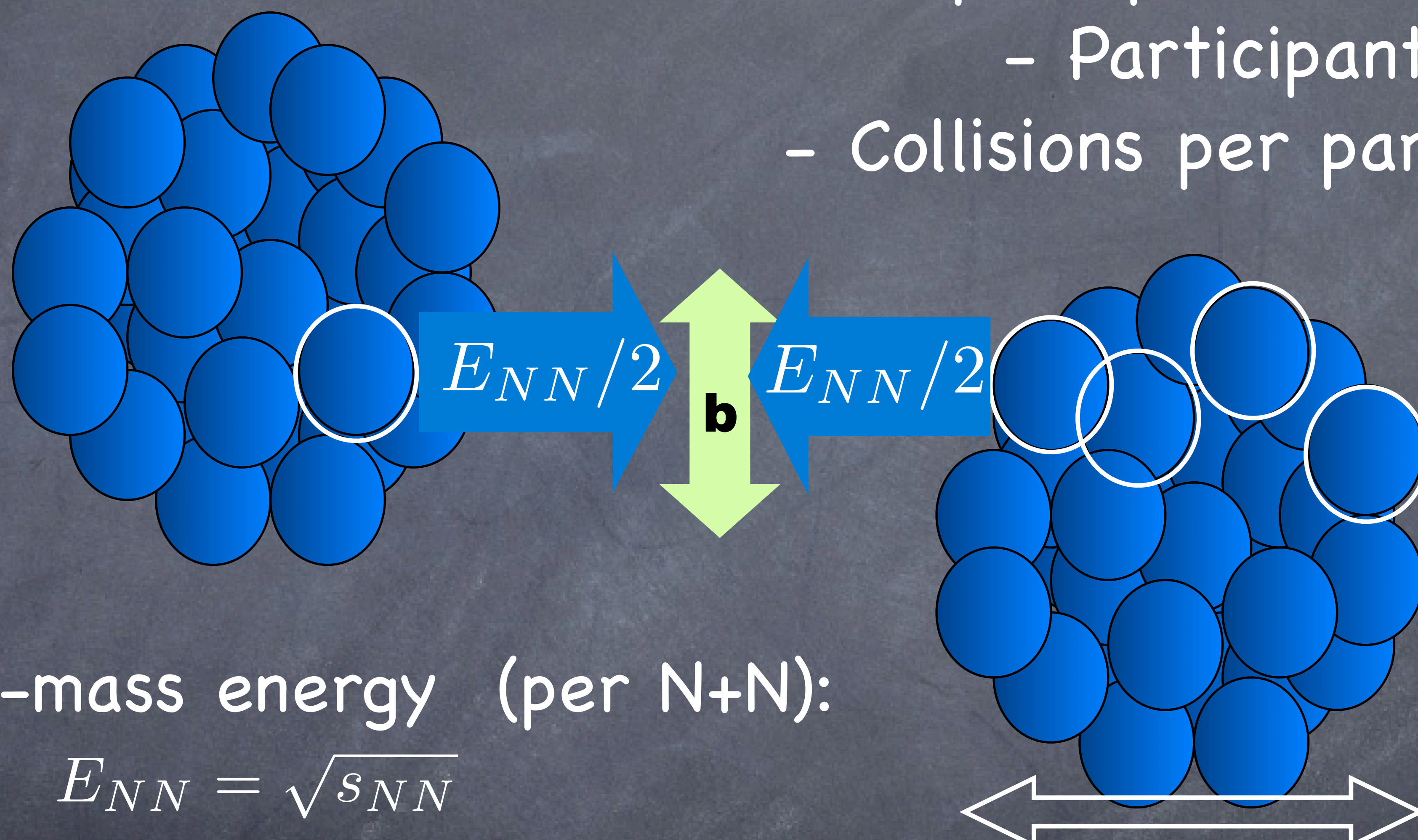

The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+
W-
Z
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

RHIC @ BNL

x <-- You are here!

What do we do @ RHIC?

Impact parameter (b):
- Participants
- Collisions per participant

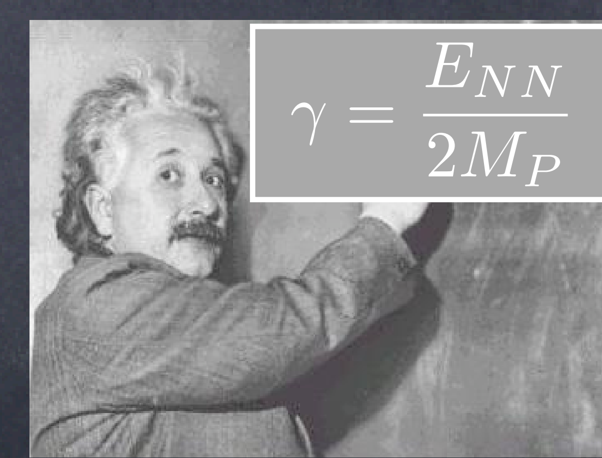


Center-of-mass energy (per N+N):

$$E_{NN} = \sqrt{s_{NN}}$$

- N+N cross section
- Lorentz contraction
- "hard" processes

$$L = \frac{L_0}{\gamma}$$

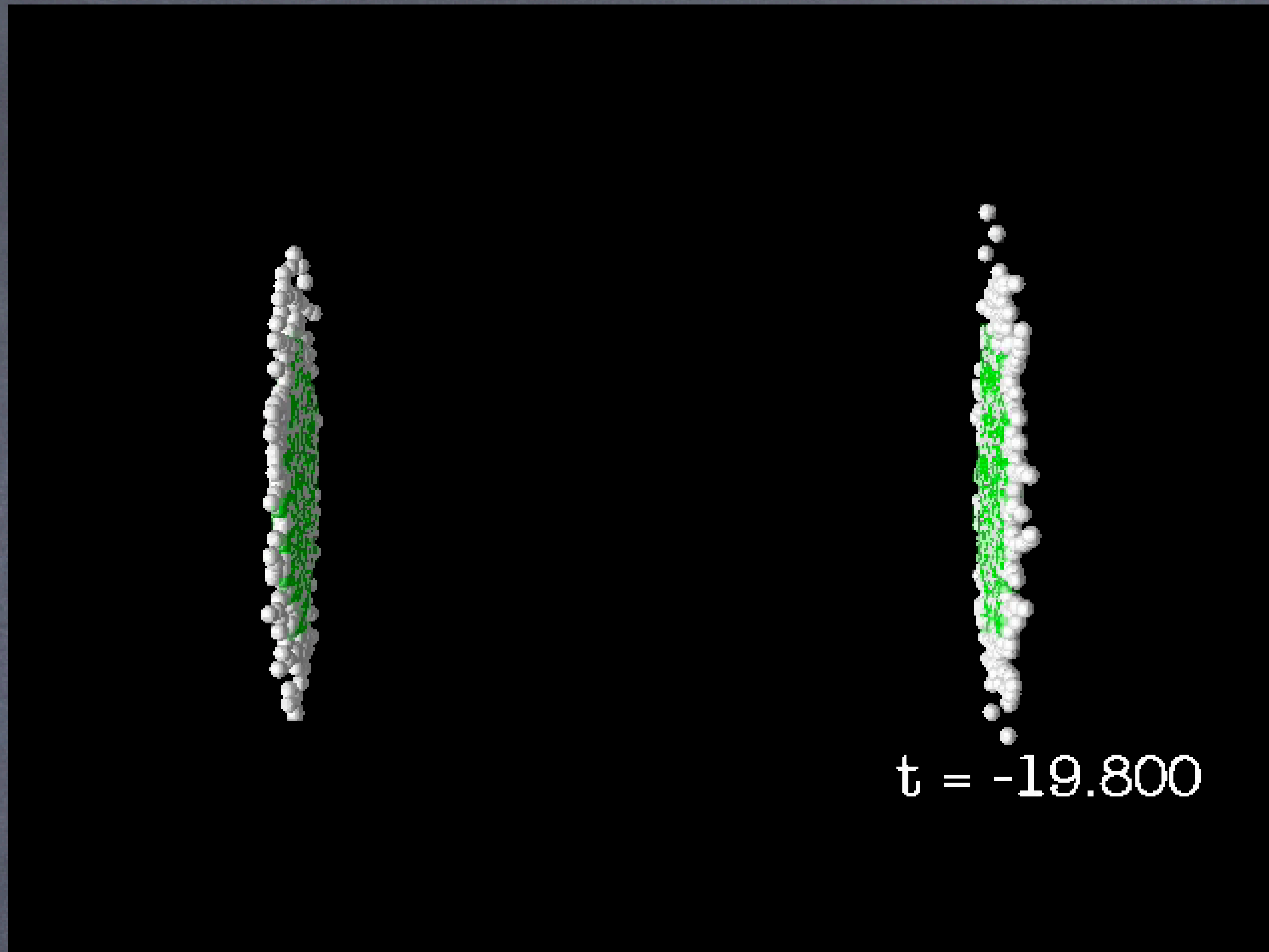


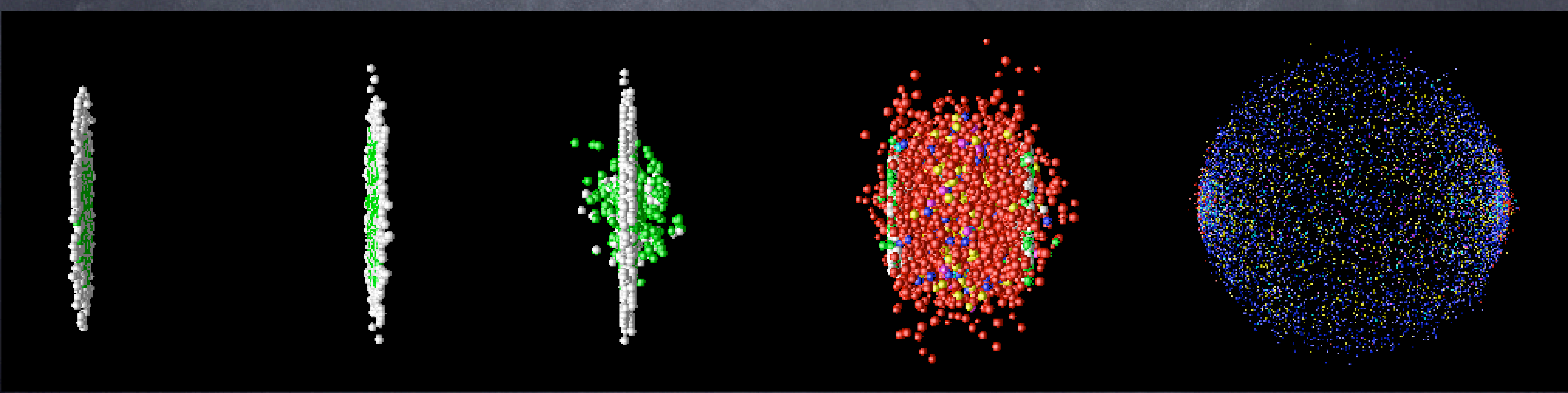
Top RHIC energy is E_{NN} = 200 GeV

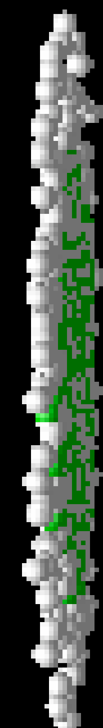
http://www.ccd.bnl.gov/visualization/gallery/au_on_au/

Units of time are

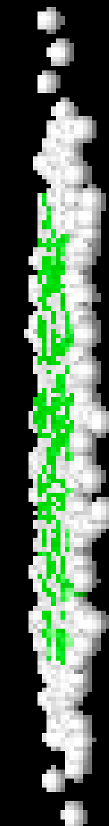
fm/c
~3×10^{-24}s
(yocto-seconds)



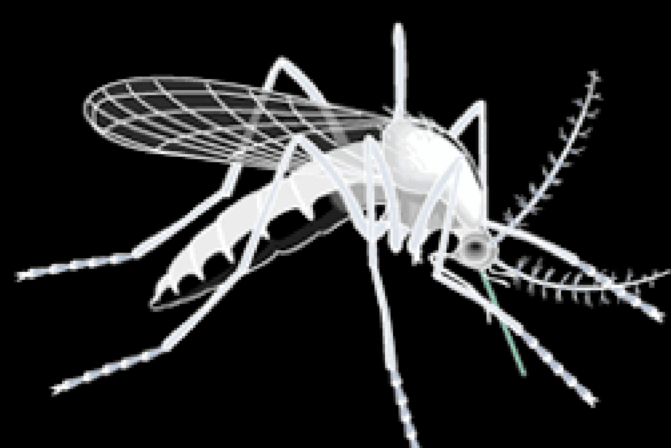




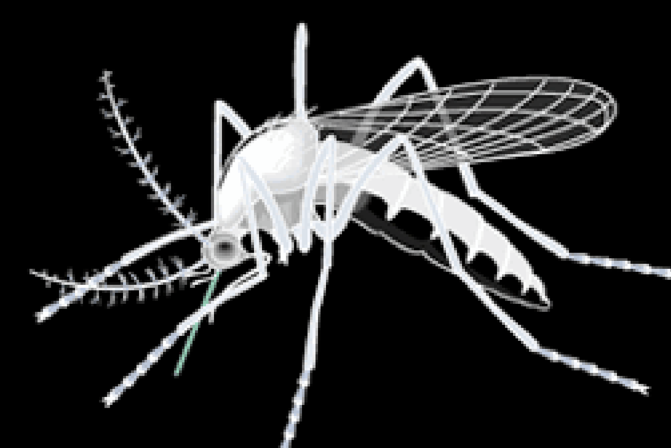
How much energy in each collision?



$$1.6 \times 10^{-19} \frac{J}{eV} \times 197 \times 200GeV \sim 6\mu J$$

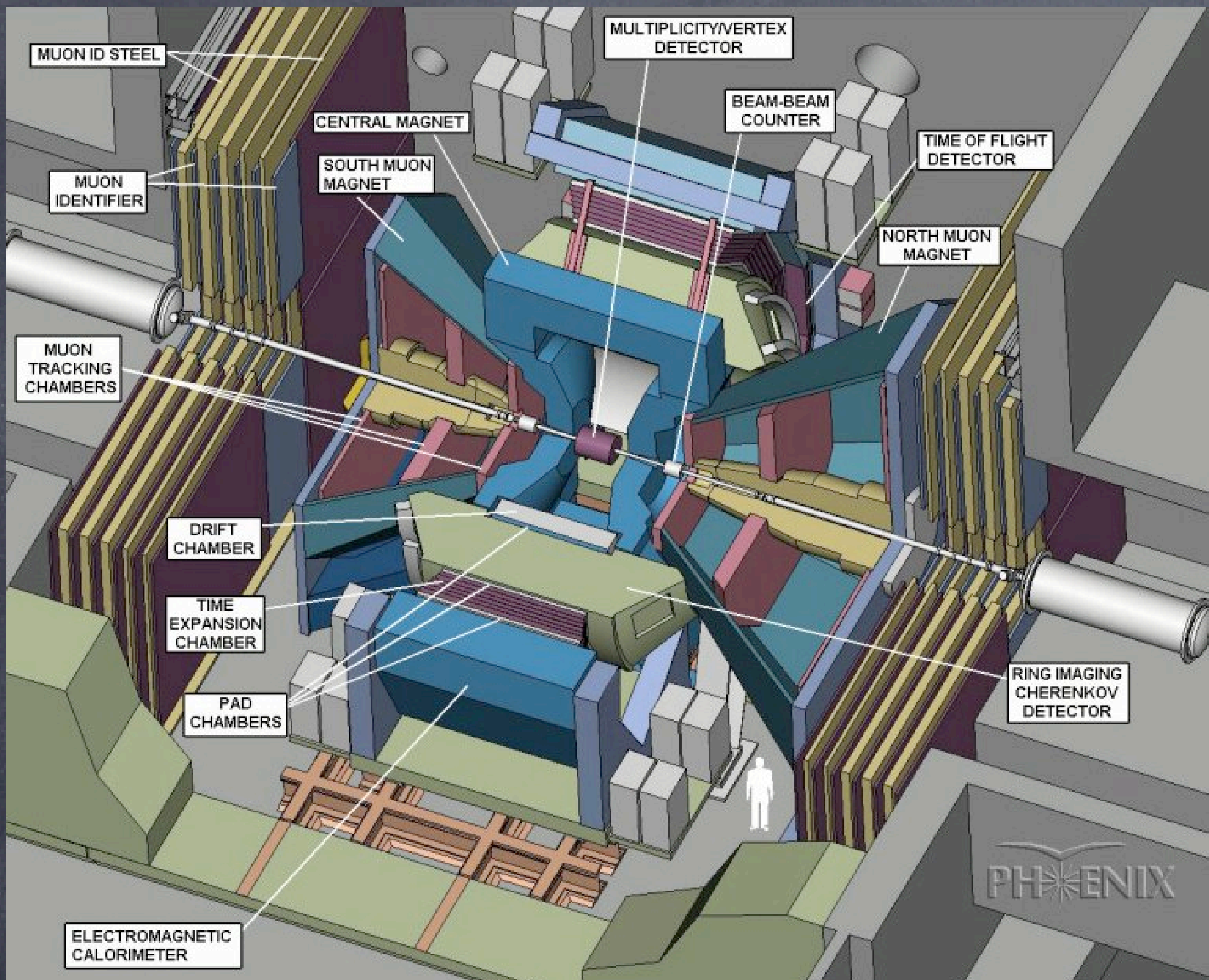


Consider two mosquitos colliding...

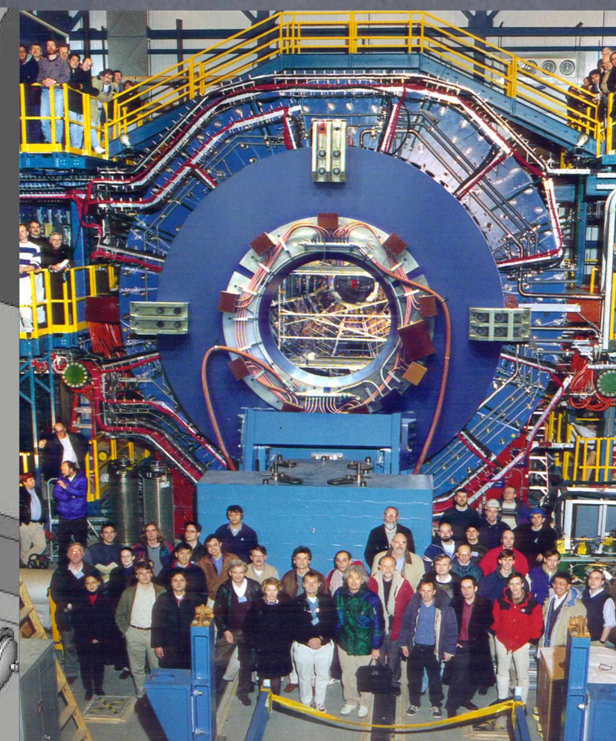


$$2 \times \frac{1}{2} mv^2 = (1g) \times (10cm/s)^2 = 10\mu J$$

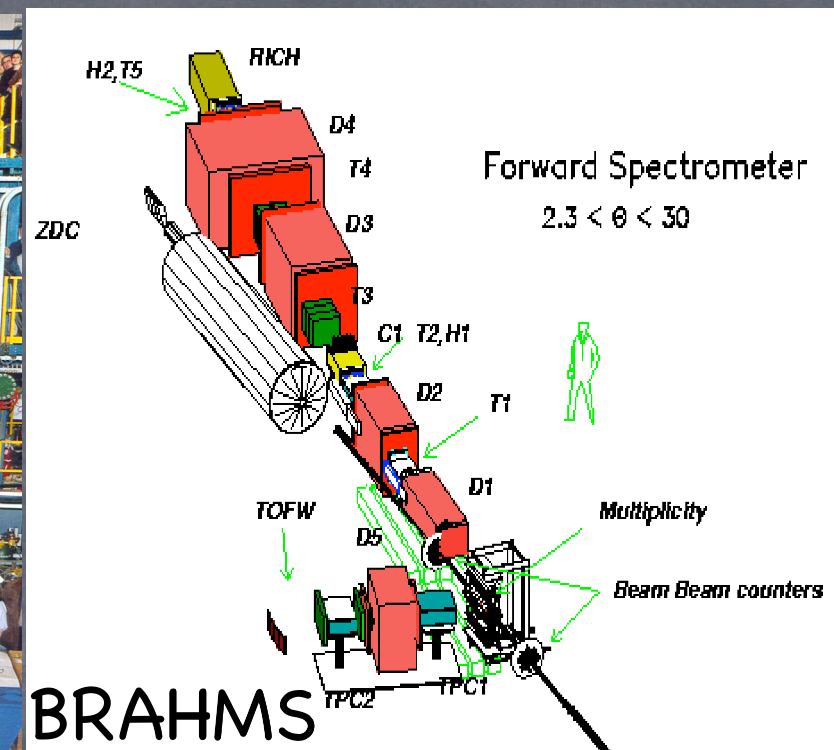
RHIC Detectors to Scale



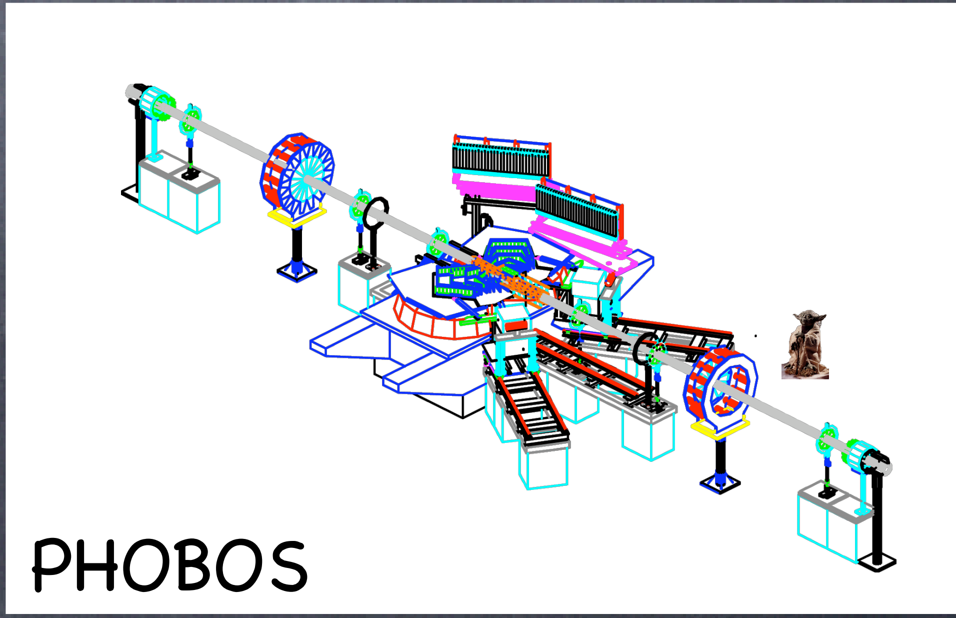
PHENIX



STAR

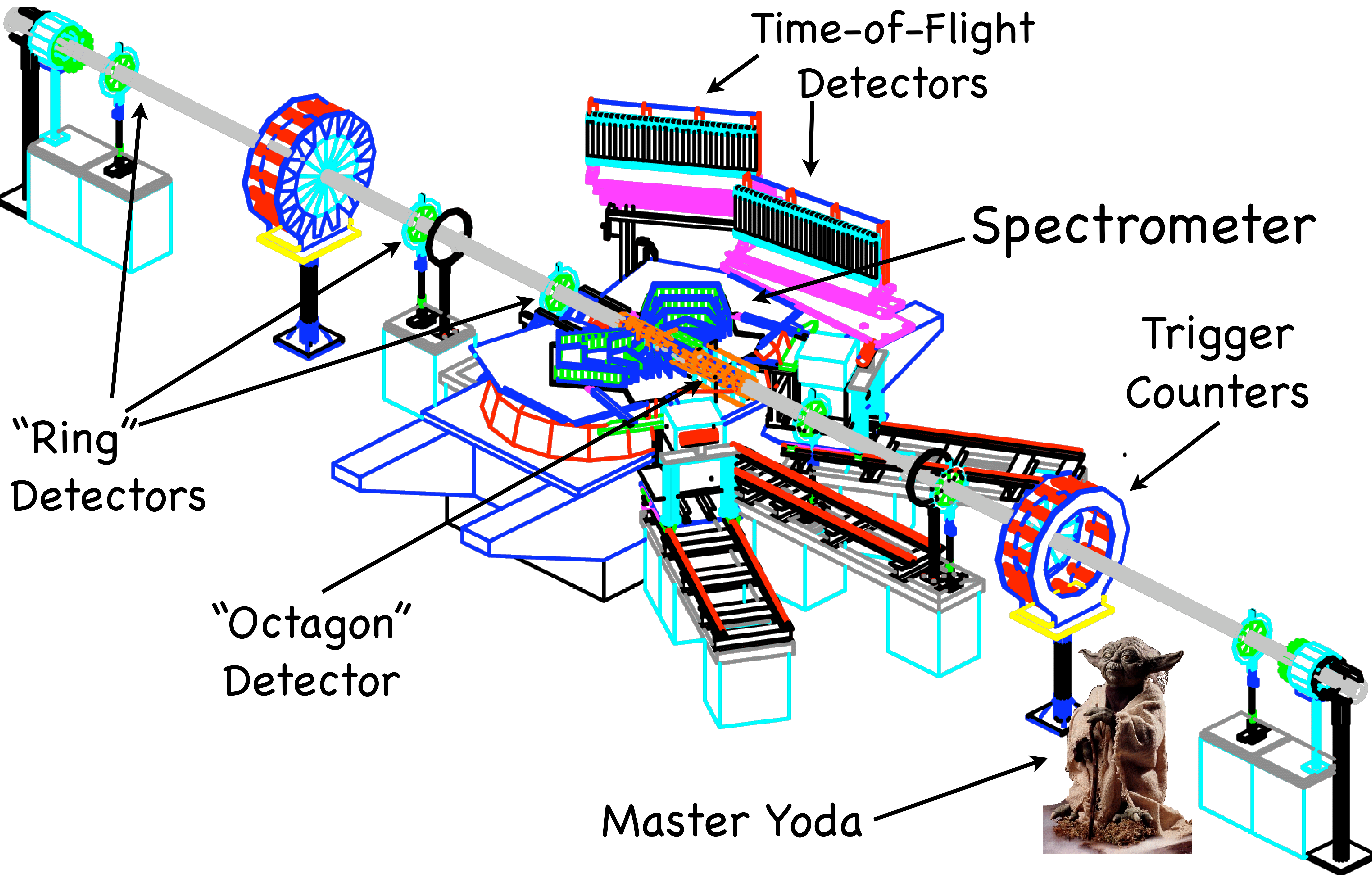


BRAHMS

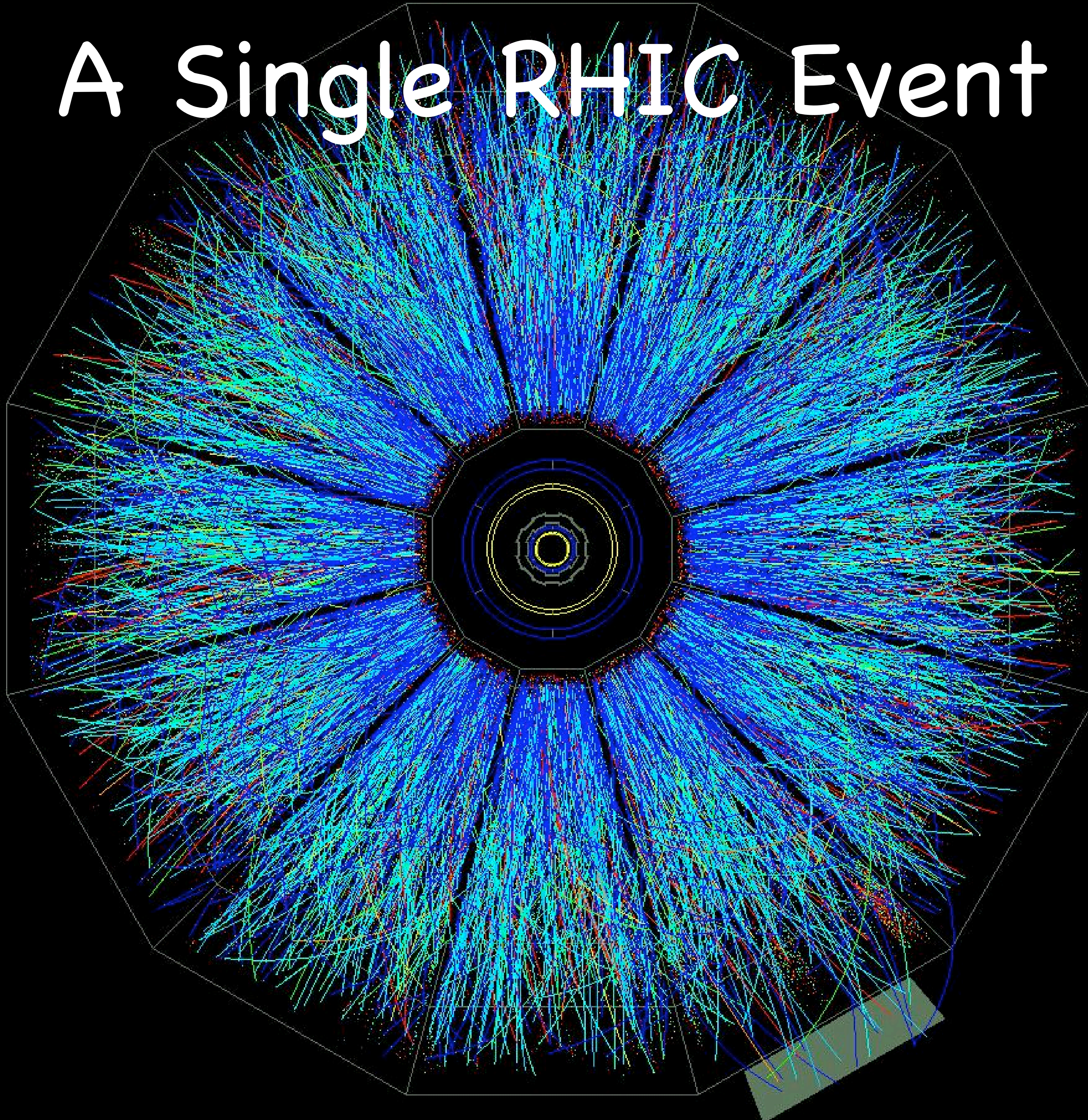


PHOBOS

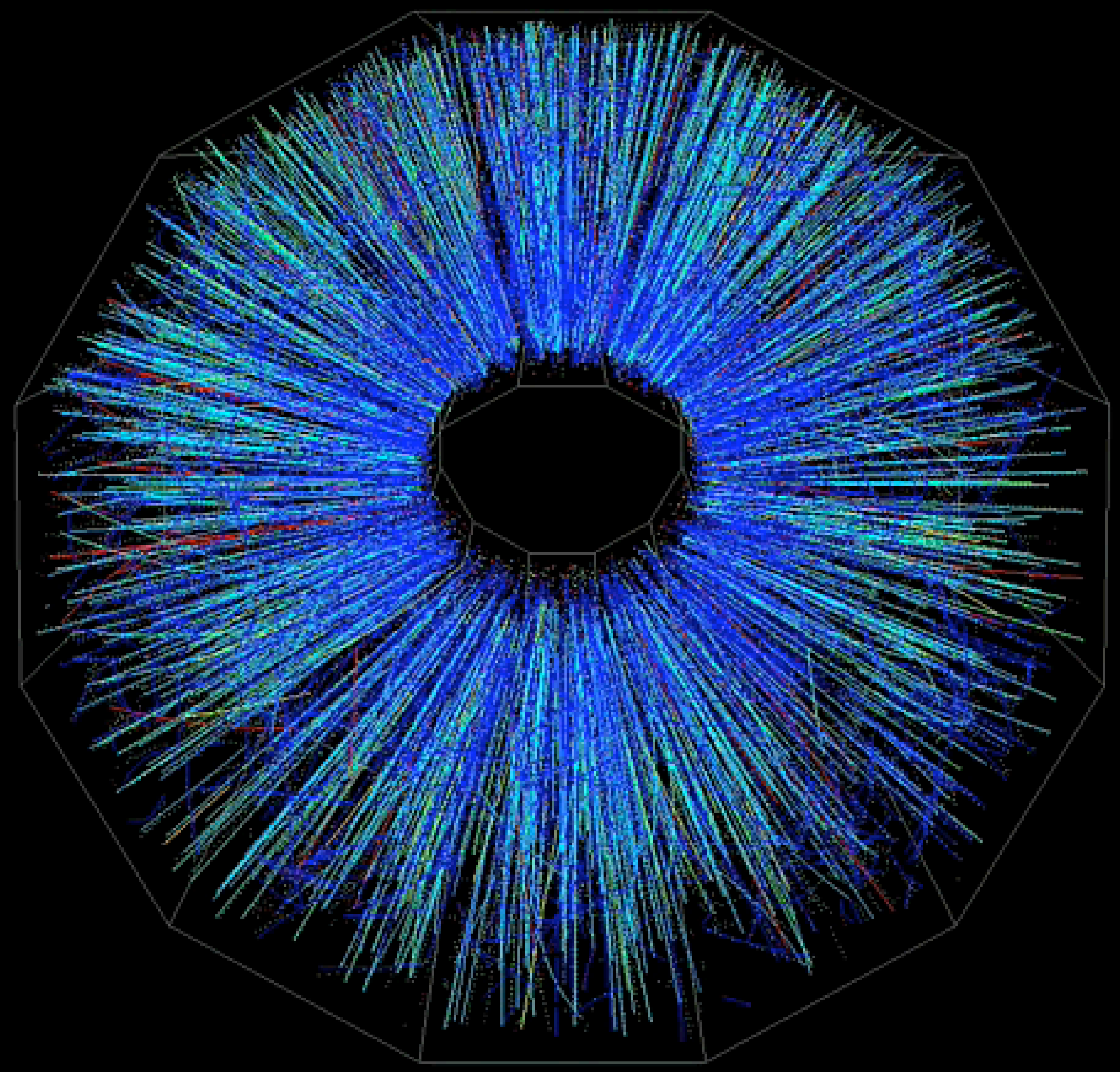
PHOBOS In Detail



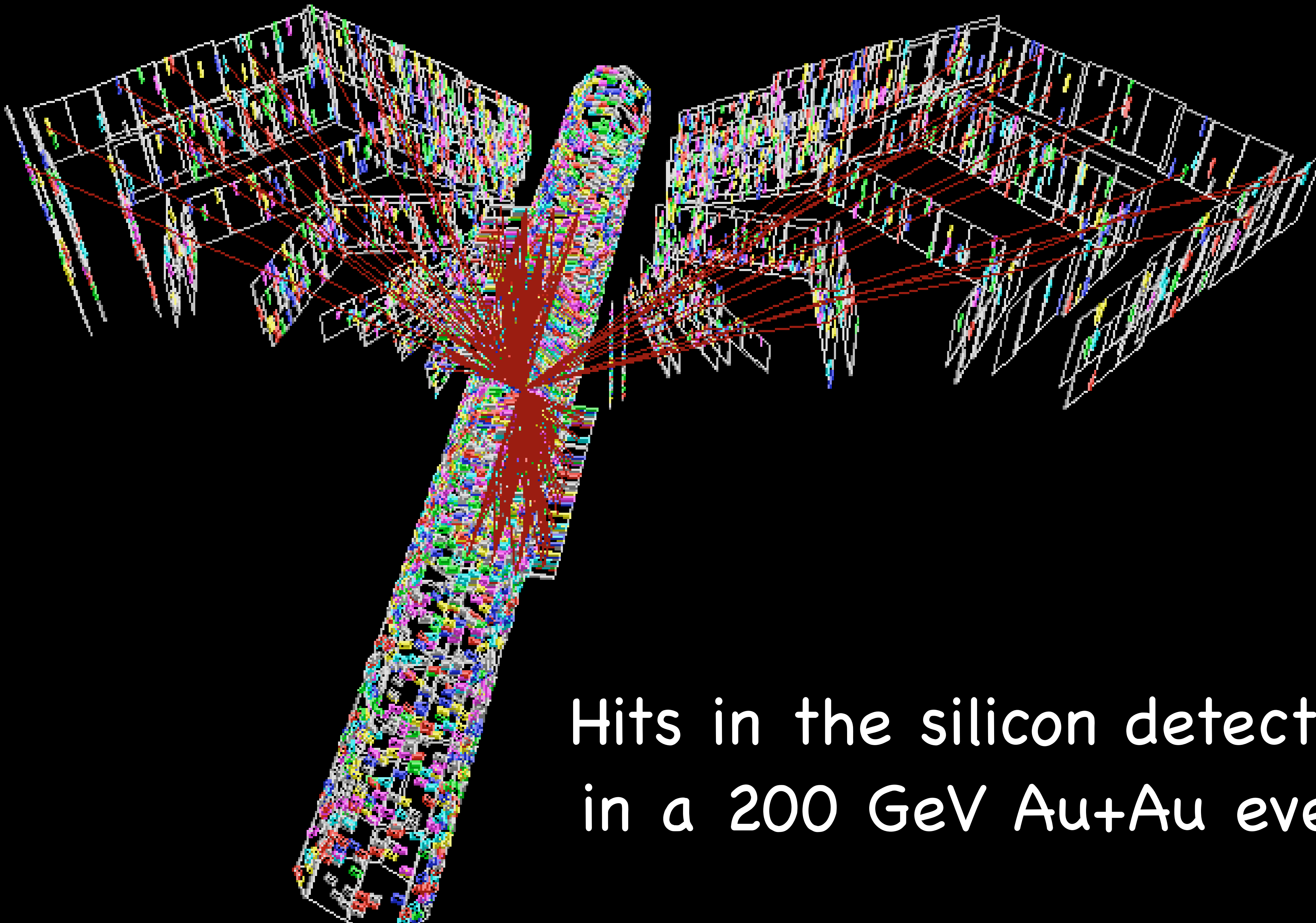
A Single RHIC Event



A Single RHIC Event

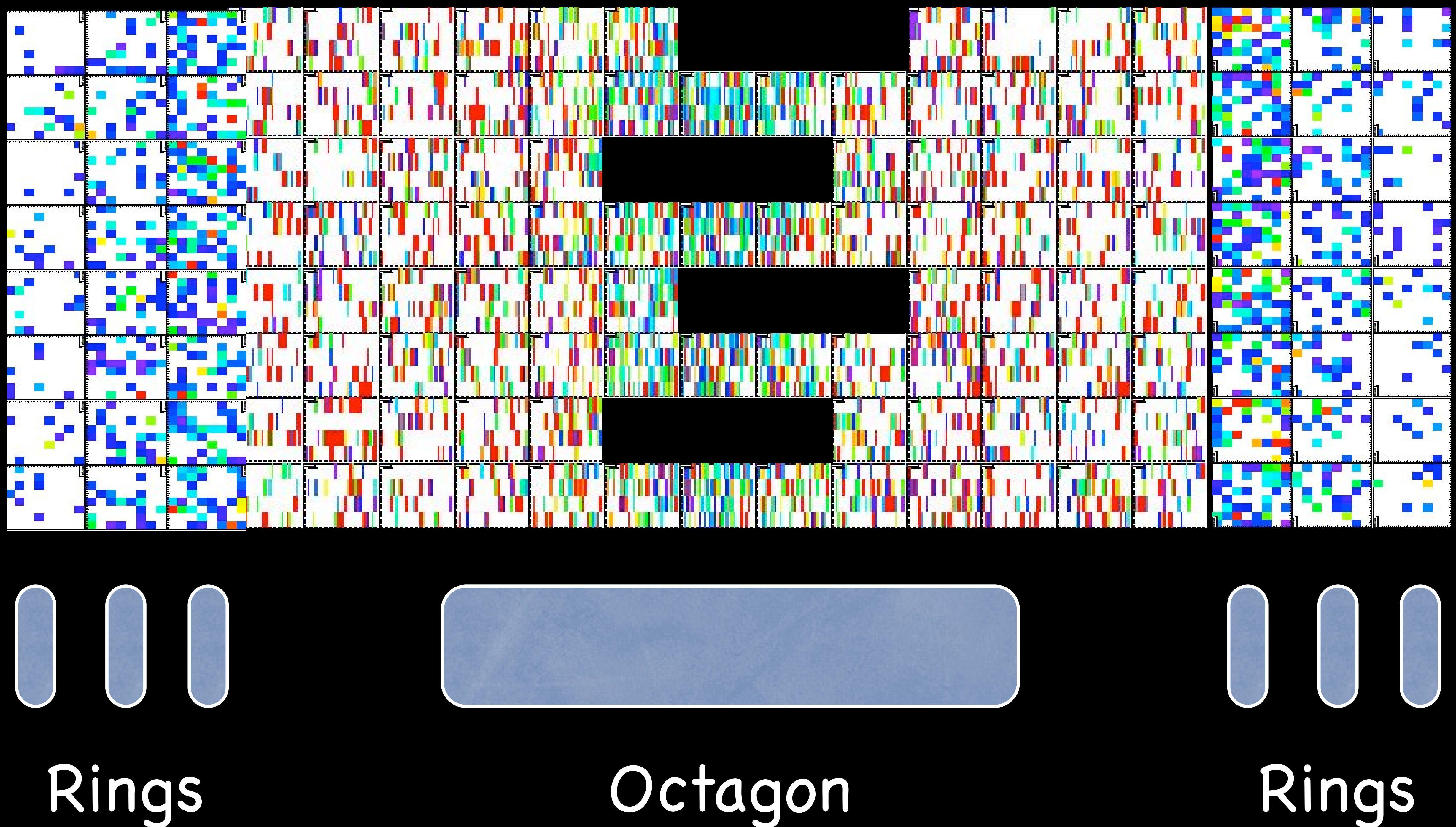


A Single Event @ PHOBOS

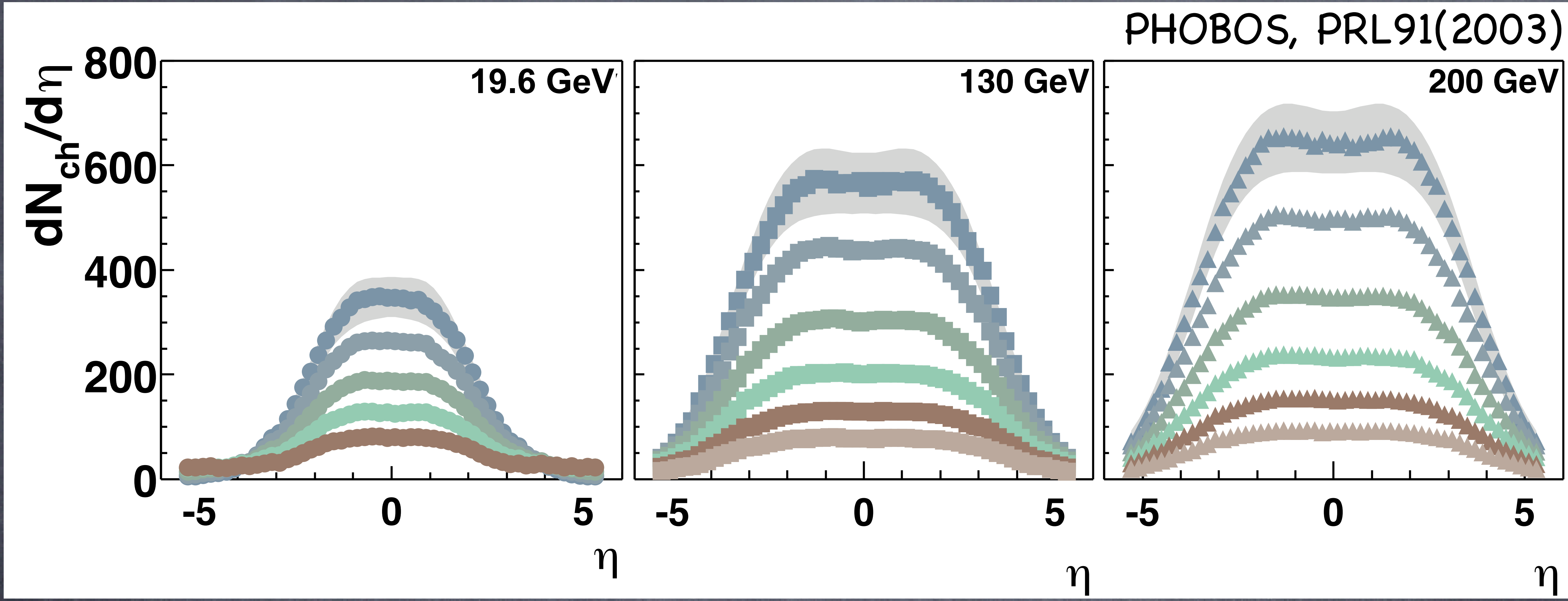


Hits in the silicon detectors
in a 200 GeV Au+Au event

One Event, Unwrapped



Pseudorapidity Distributions



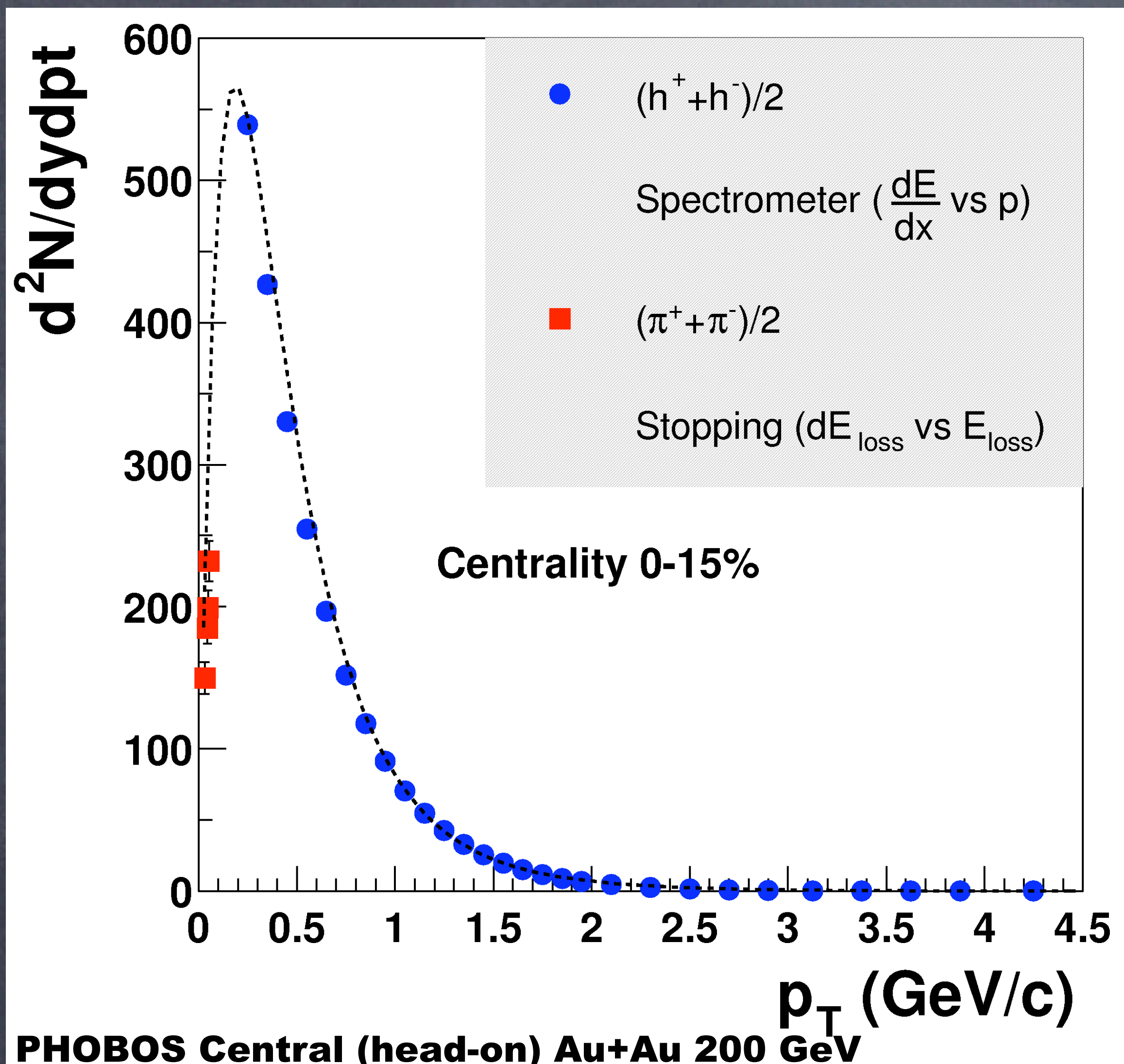
$$y = tanh^{-1}\beta_z \longrightarrow \eta = -\log(\tan(\theta/2))$$

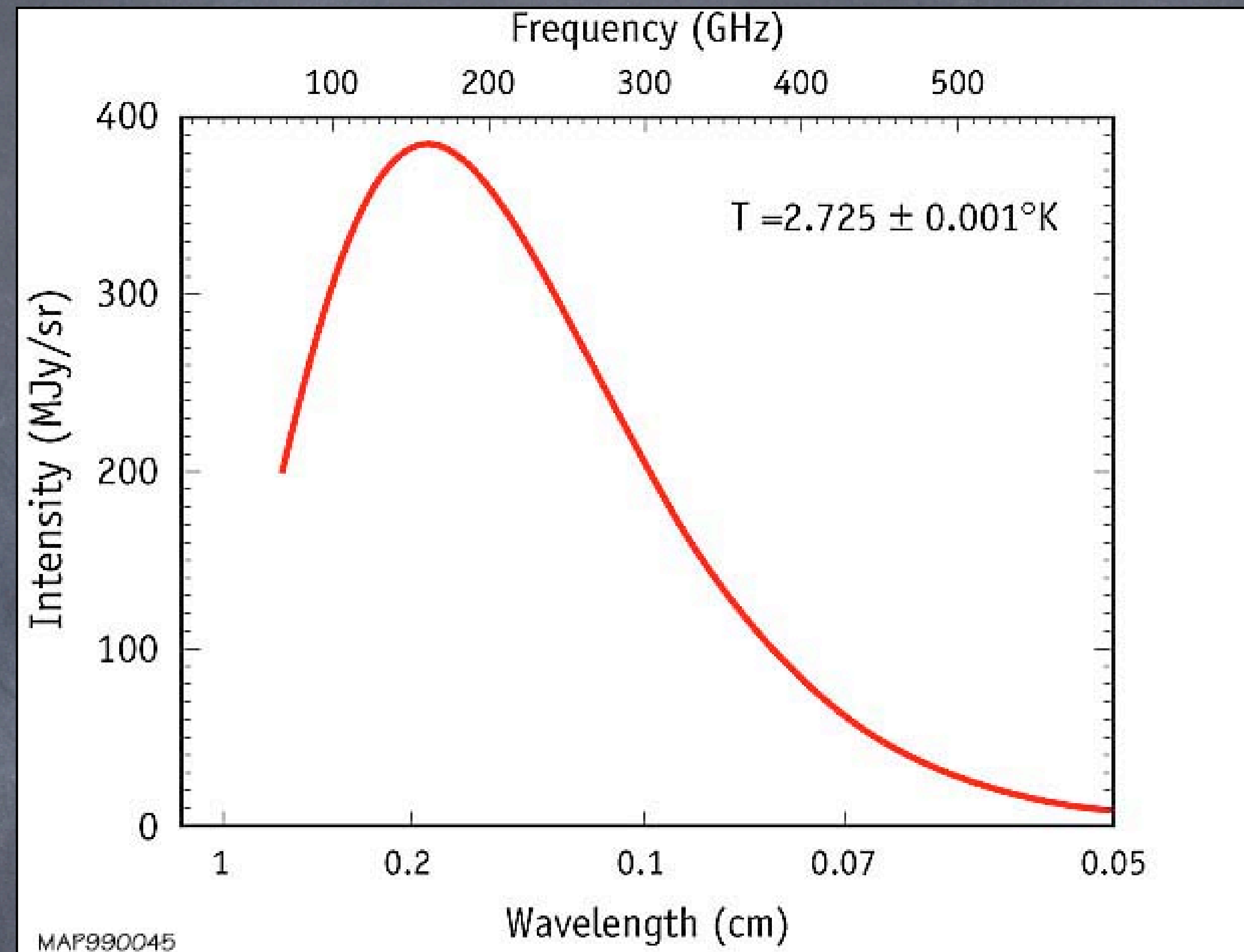
Angle tells us about velocity of particles.
Most produced particles are relatively slow.
$E=mc^2$: Trade off of kinetic energy for matter

What can we learn about the dynamics of the "middle ages" by considering the simple features of the initial & final states?

Let's start with final state, after all of the dynamics has finished ("frozen out", a concept from cosmology...)

Strong Blackbody





System looks like a "blackbody", with hadrons (mesons & baryons) instead of photons

Hadronic Fireball

Remember that we have many hadronic degrees of freedom in nature.

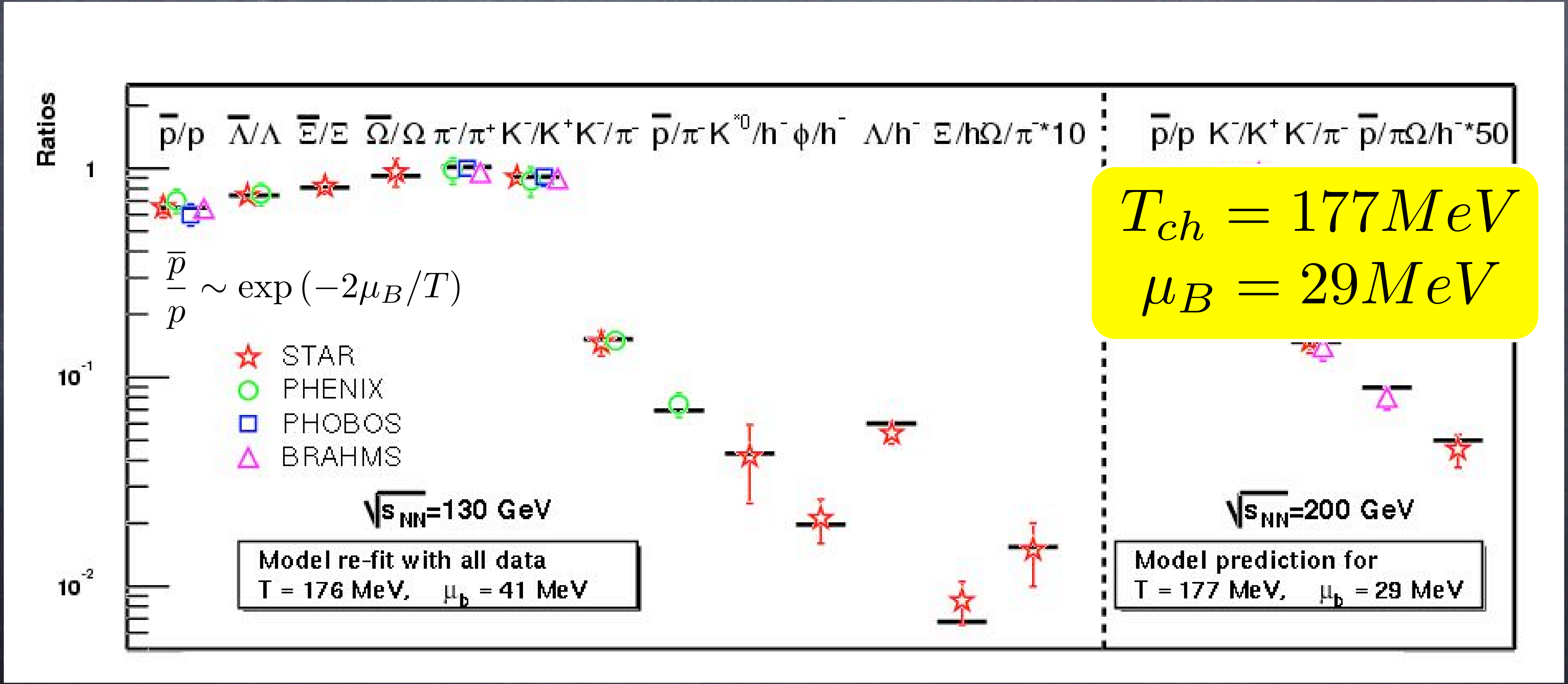
Are they radiated as if by the same temperature?

Thermochemistry at RHIC

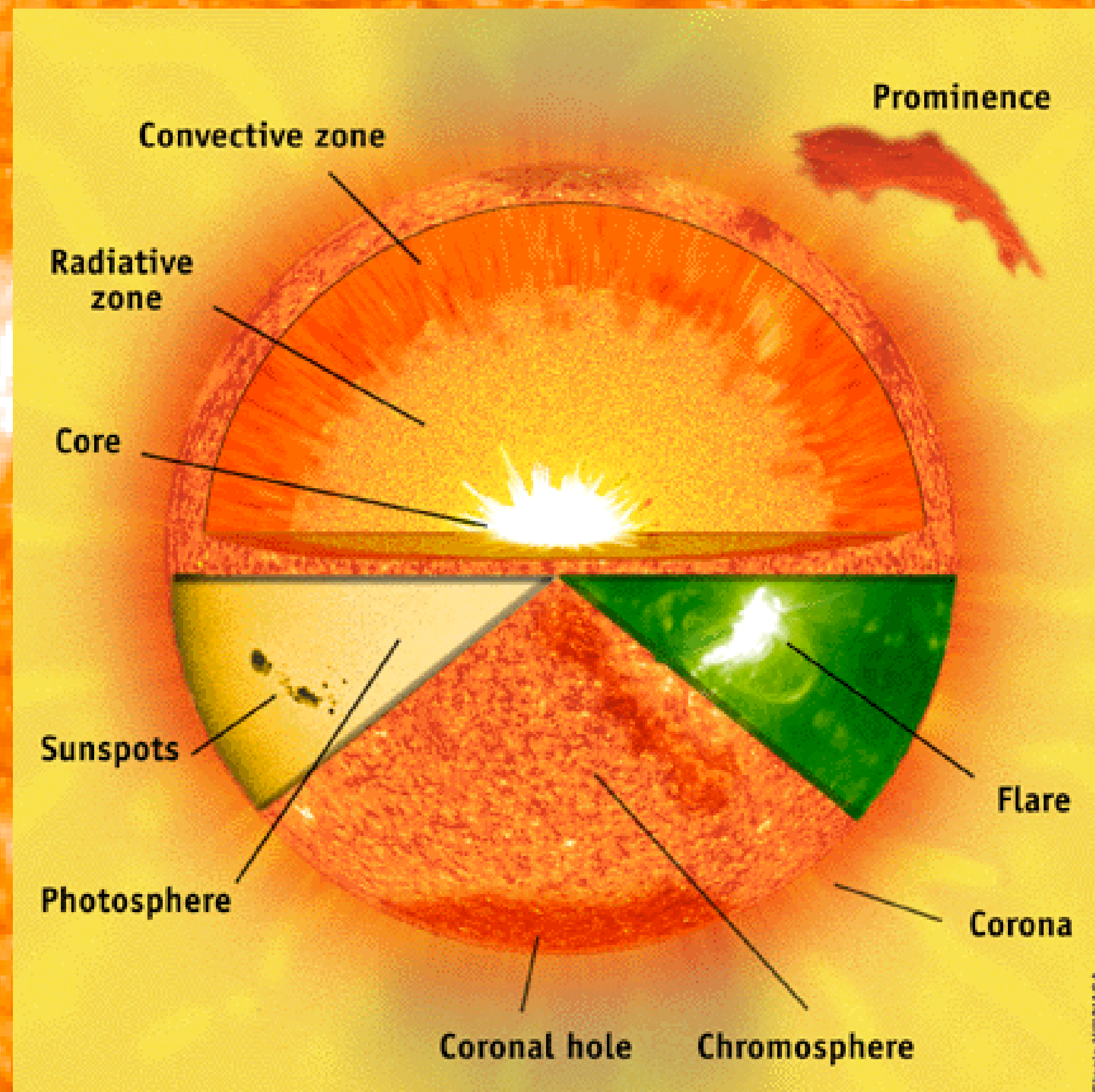
T	Chemical freezeout temperature
μ_B	Baryochemical potential
γ_s	Strangeness suppression

$$N_i \propto g_i V \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{(\sqrt{p^2+m^2}-\mu_B)/T} \pm 1}$$

$$i = \pi, K, p, \bar{p}, \Lambda, \bar{\Lambda}, \Sigma, \Xi, \Omega, \ldots$$



“Temperature” of the Sun



Core of the sun is 13-25 million °K

Surface of the sun is 7000°K

“Temperature” of RHIC

$$\boxed{\begin{array}{c} T_{ch} = 177 MeV \\ \mu_B = 29 MeV \end{array}}$$

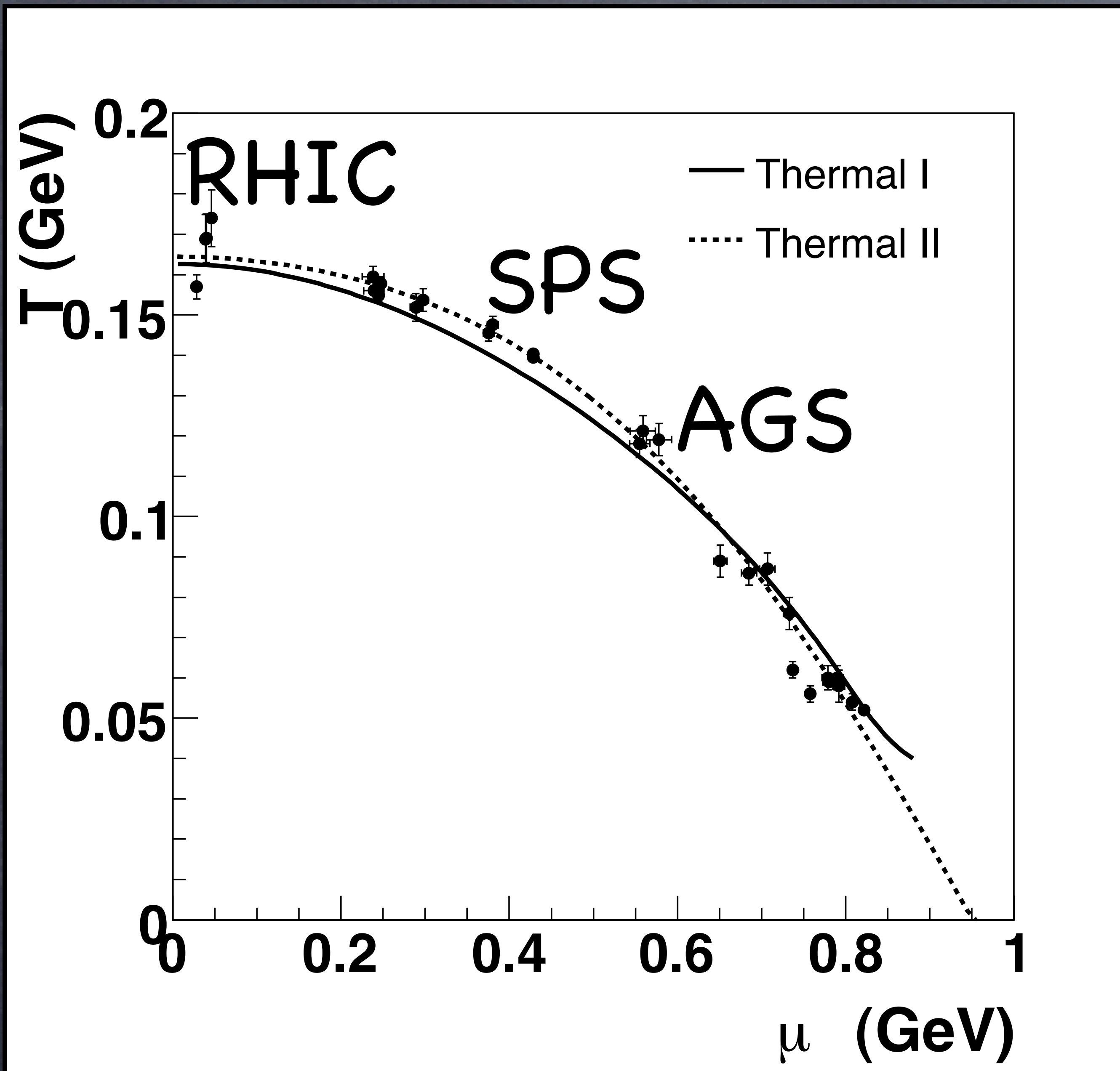
π

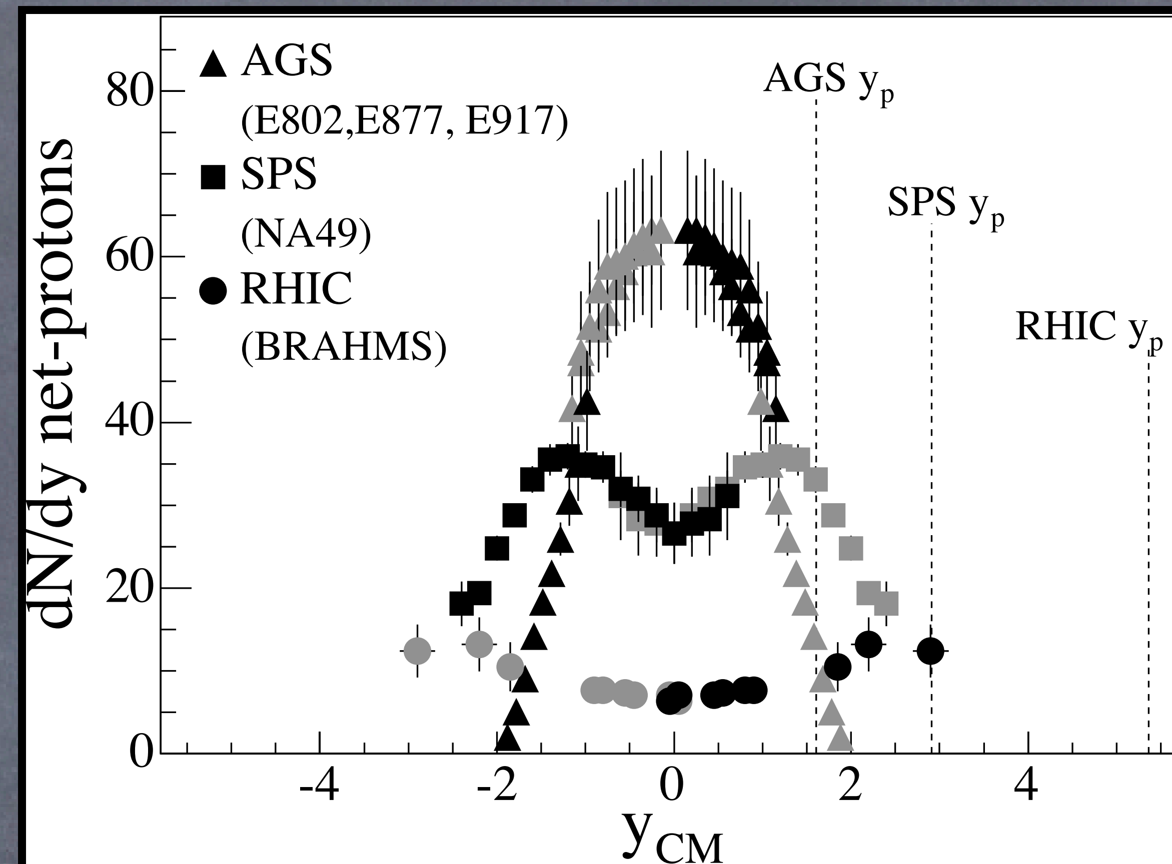
This is ~2x10^{12} degrees K

This is, in some sense, the “surface temperature” of a RHIC collision, when it “freezes” into hadrons

The “core” must have been <u>much</u> hotter!

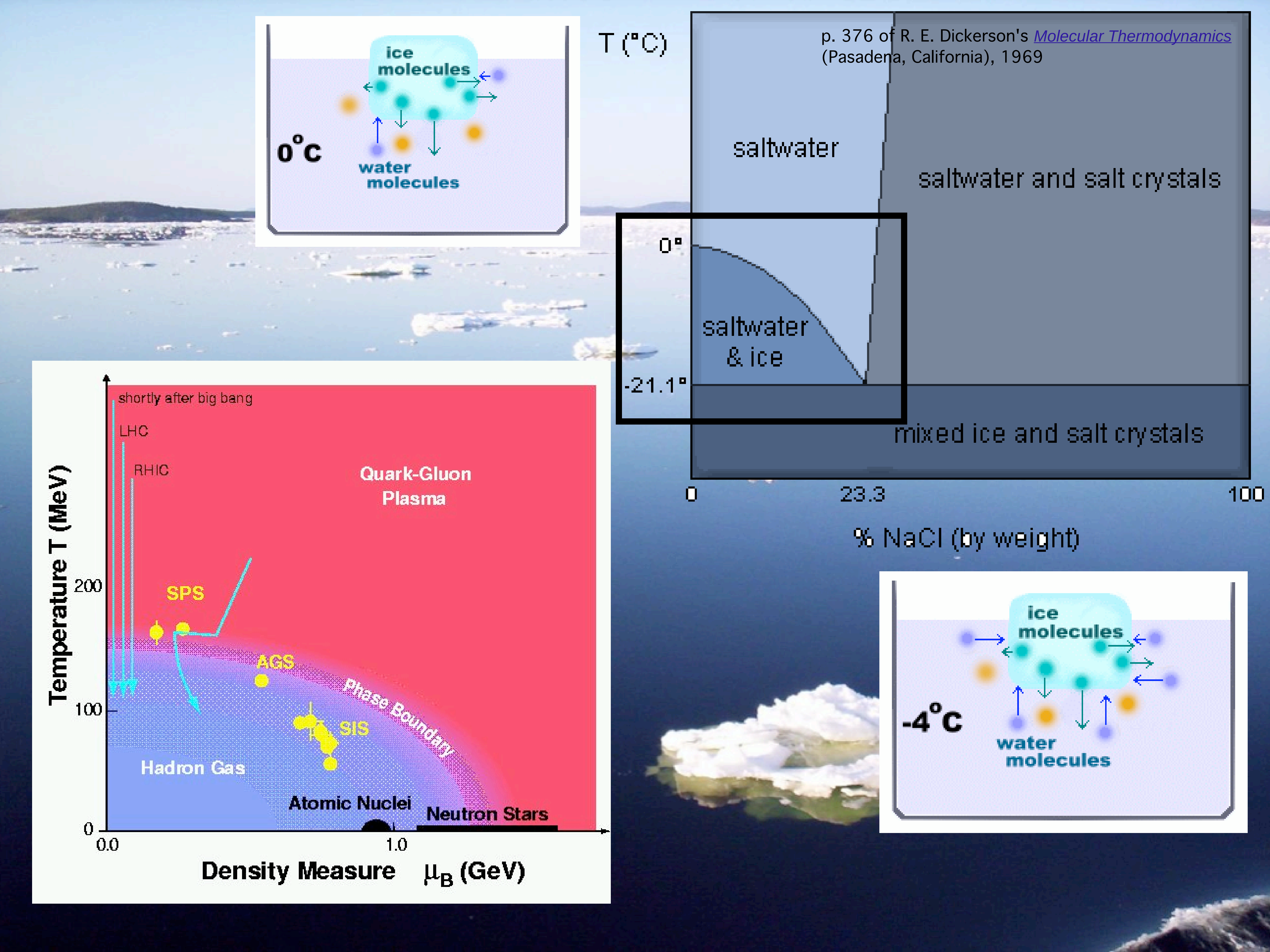
Baryochemistry



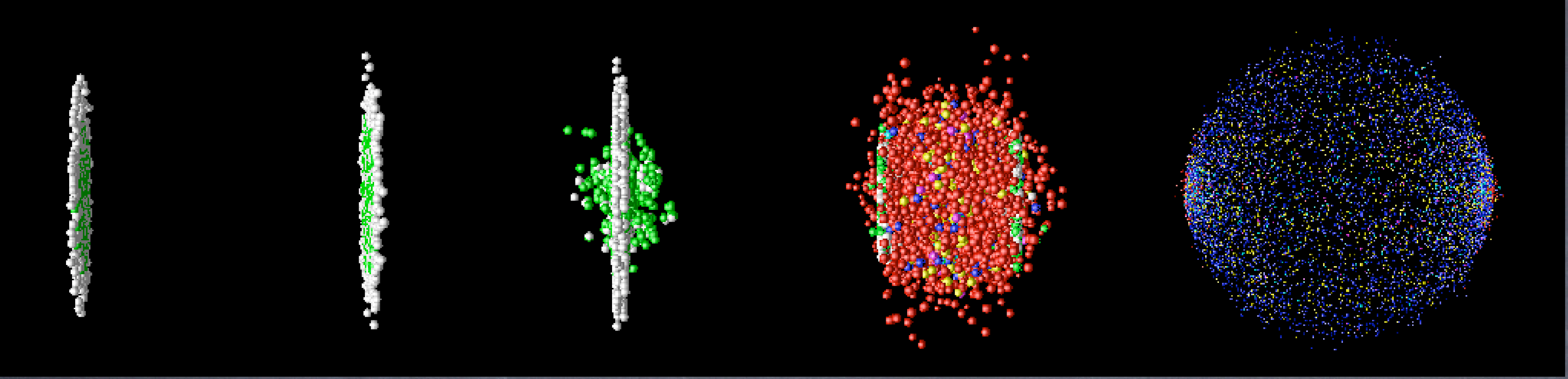


At lower energies, μ_B increases. More baryons to conserve in final state

Can be seen directly in densities of "net protons" (protons-antiprotons): at low energies, more "slow" baryons



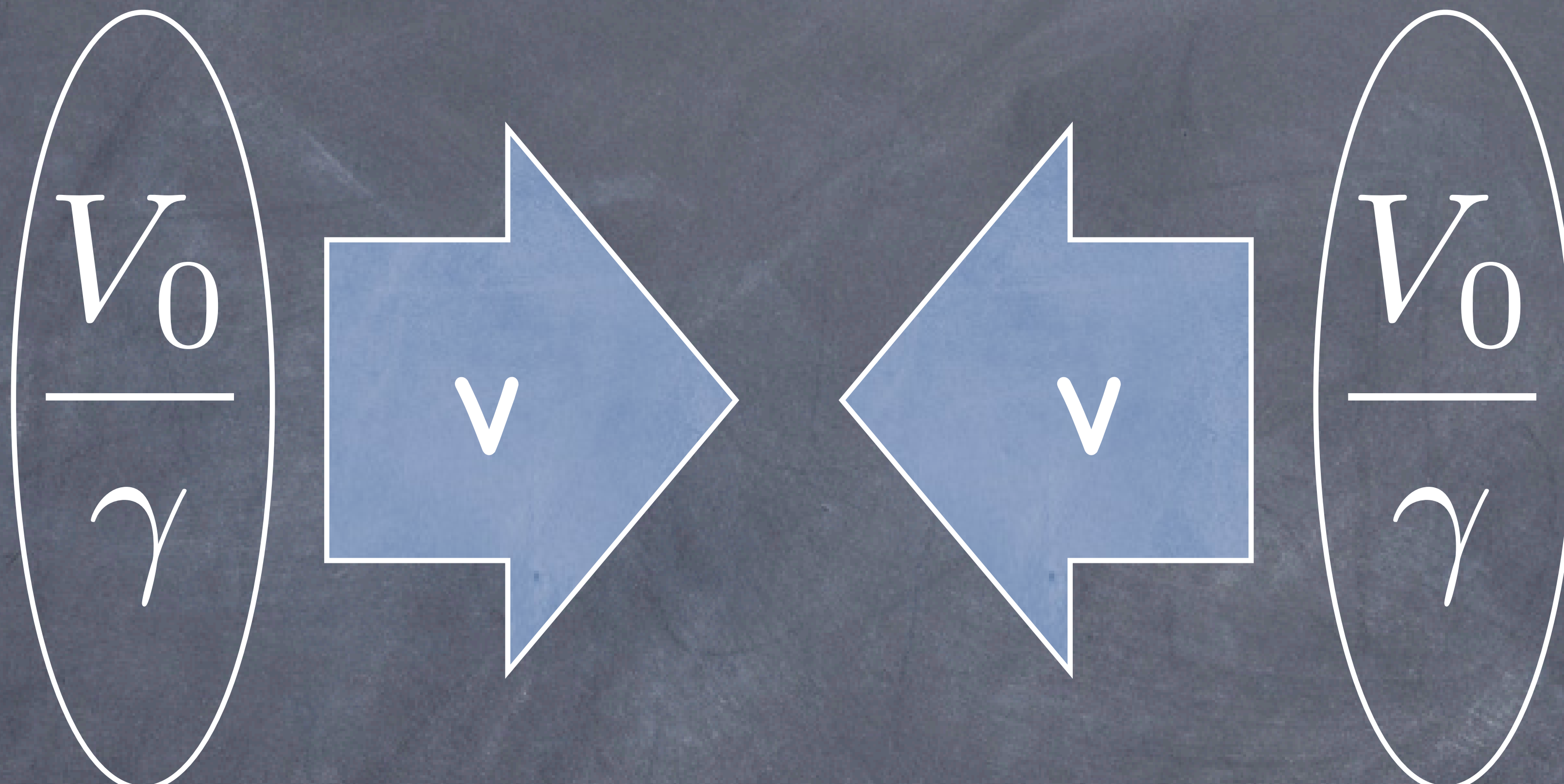
ice
molecules
0°c
water
molecules
T (°C)
p. 376 of R. E. Dickerson's Molecular Thermodynamics
(Pasadena, California), 1969
saltwater
saltwater and salt crystals
0°
saltwater
& ice
-21.1°
mixed ice and salt crystals
0
23.3
100
% NaCl (by weight)
shortly after big bang
LHC
RHIC
Quark-Gluon
Plasma
Temperature T (MeV)
200
100
0
SPS
AGS
Phase Boundary
SIS
Hadron Gas
Atomic Nuclei
Neutron Stars
0.0
1.0
Density Measure μB (GeV)
ice
molecules
-4°c
water
molecules



But what about the entropy $S = \frac{\Delta Q}{T}$?

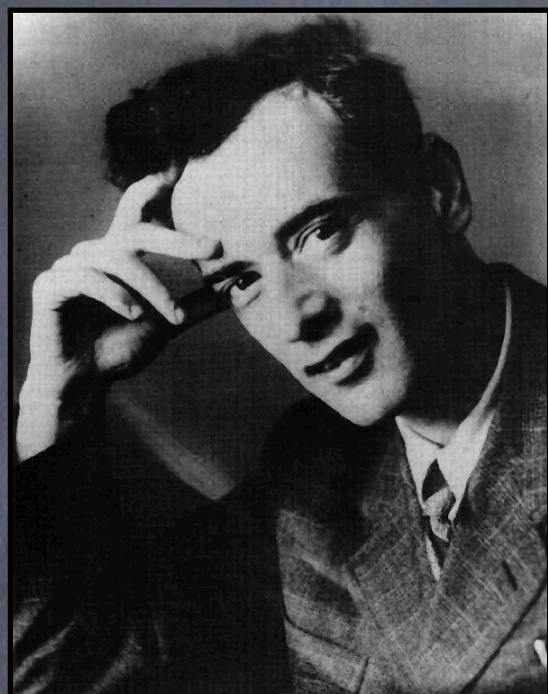
Various degrees of freedom could be important at different phases of the evolution (baryons, quarks/gluons, hadrons, etc.)

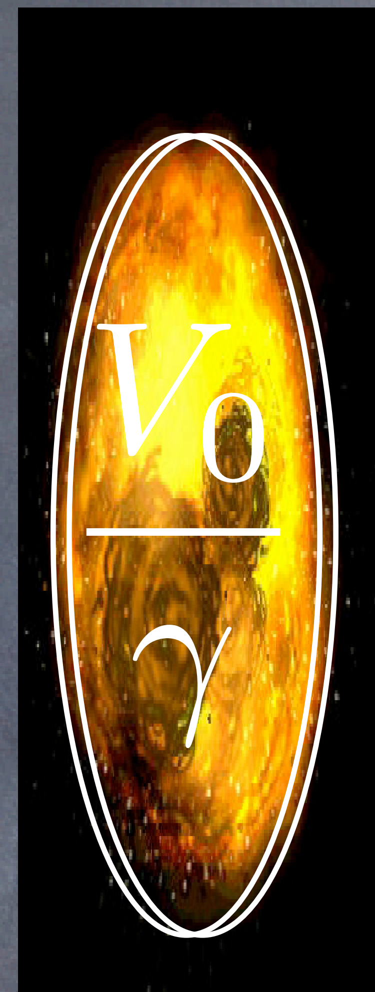
A Simple Model

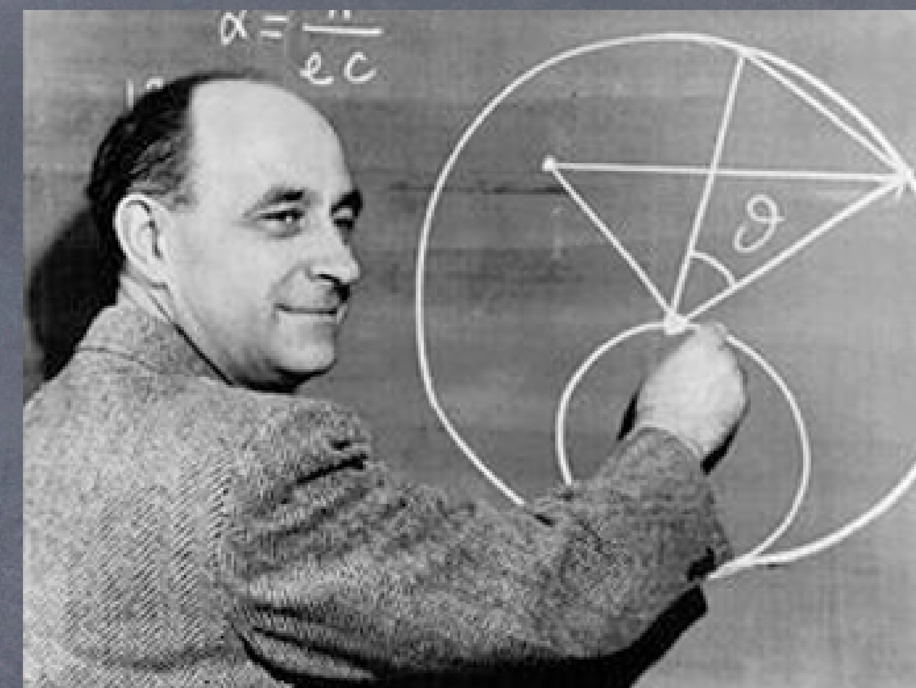


Colliding nuclei boosted by velocity v

Landau & Fermi's Approach







Assume <u>nothing</u> about dynamics or degrees of freedom except they rapidly and efficiently thermalize <u>all of the energy</u> in the overlap <u>volume</u>

At RHIC, this thermalization time is <u>very</u> short: 0.1 fm/c!

Total Entropy Calculation

Energy Density

$$\boxed{\epsilon = \frac{E}{V}}$$

$$V = \frac{V_0}{\gamma} = \frac{2M_P V_0}{E_{NN}}$$

$$\boxed{= \frac{E_{NN}^2}{2M_P V_0}}$$

4 TeV/fm3 @ RHIC!

Assume blackbody radiation formulae

$$P = \frac{\epsilon}{3} \Rightarrow \boxed{s \propto \epsilon^{3/4}}$$

Entropy Density

$$V \quad \boxed{S = sV} \propto \frac{\left(E_{NN}^2\right)^{3/4}}{E_{NN}} \boxed{= E_{NN}^{1/2}}$$

Total Multiplicity

$$\boxed{N_{ch} \propto N \propto S \propto \sqrt{E_{NN}}}$$

Charged Particles

are a fixed fraction of

Total Number of Particles

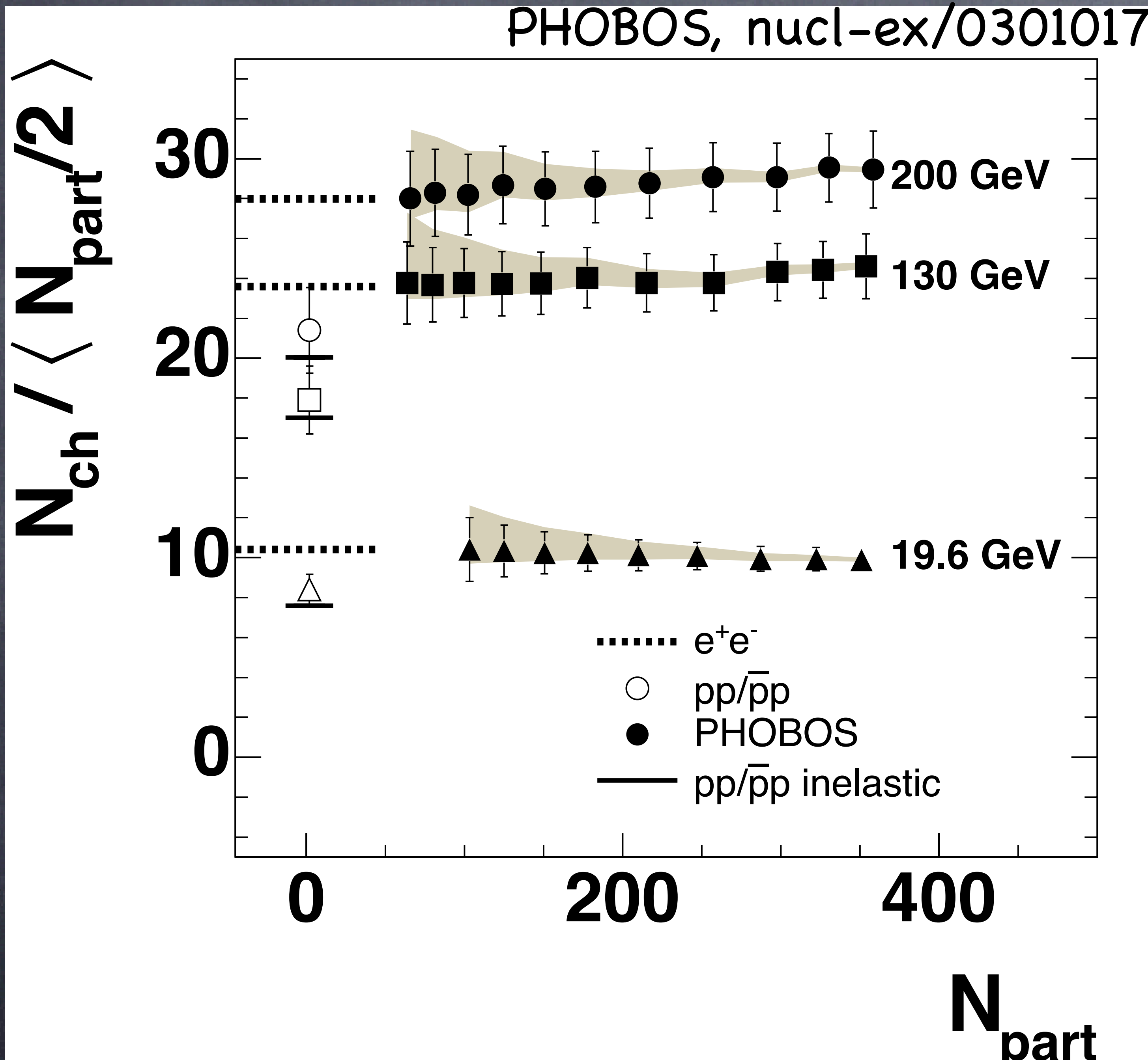
which are proportional to

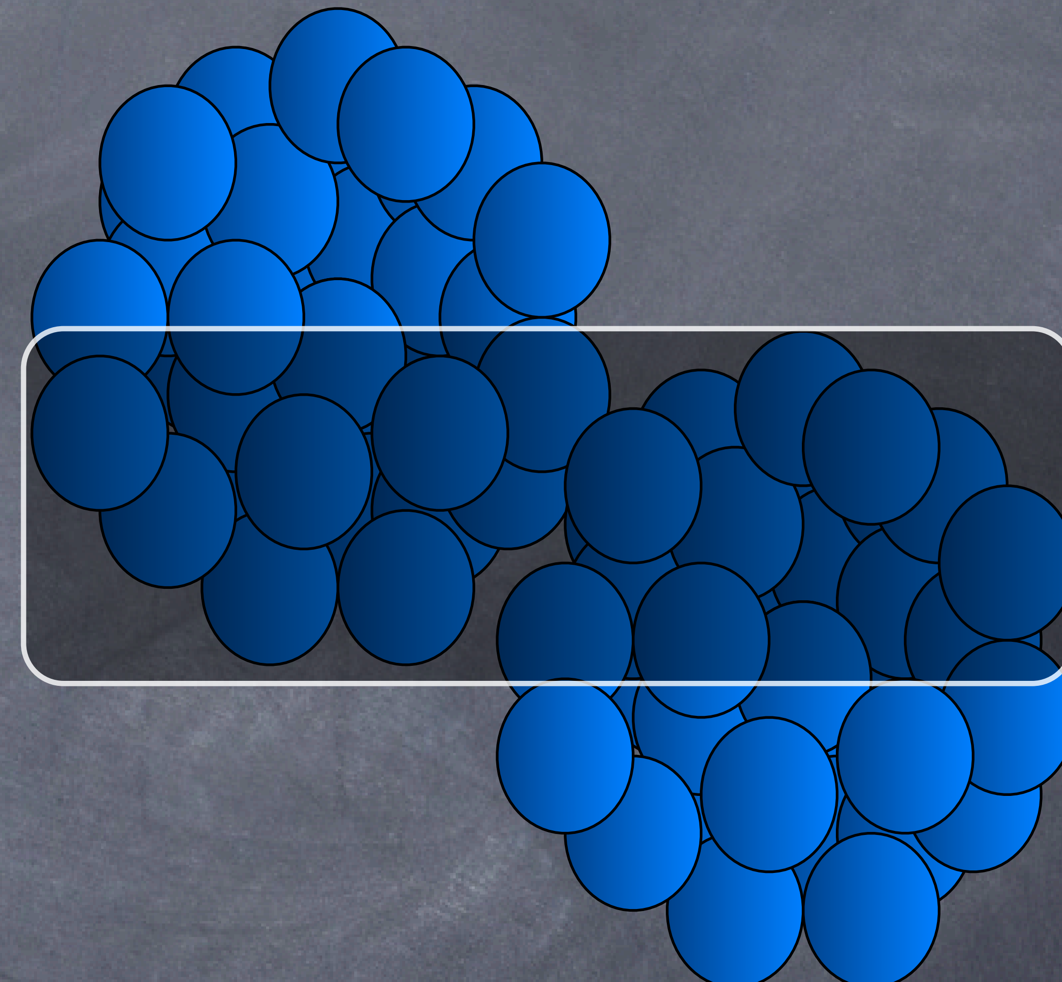
the Total Entropy

which scales as

The square-root of the Available Energy

Total Multiplicity

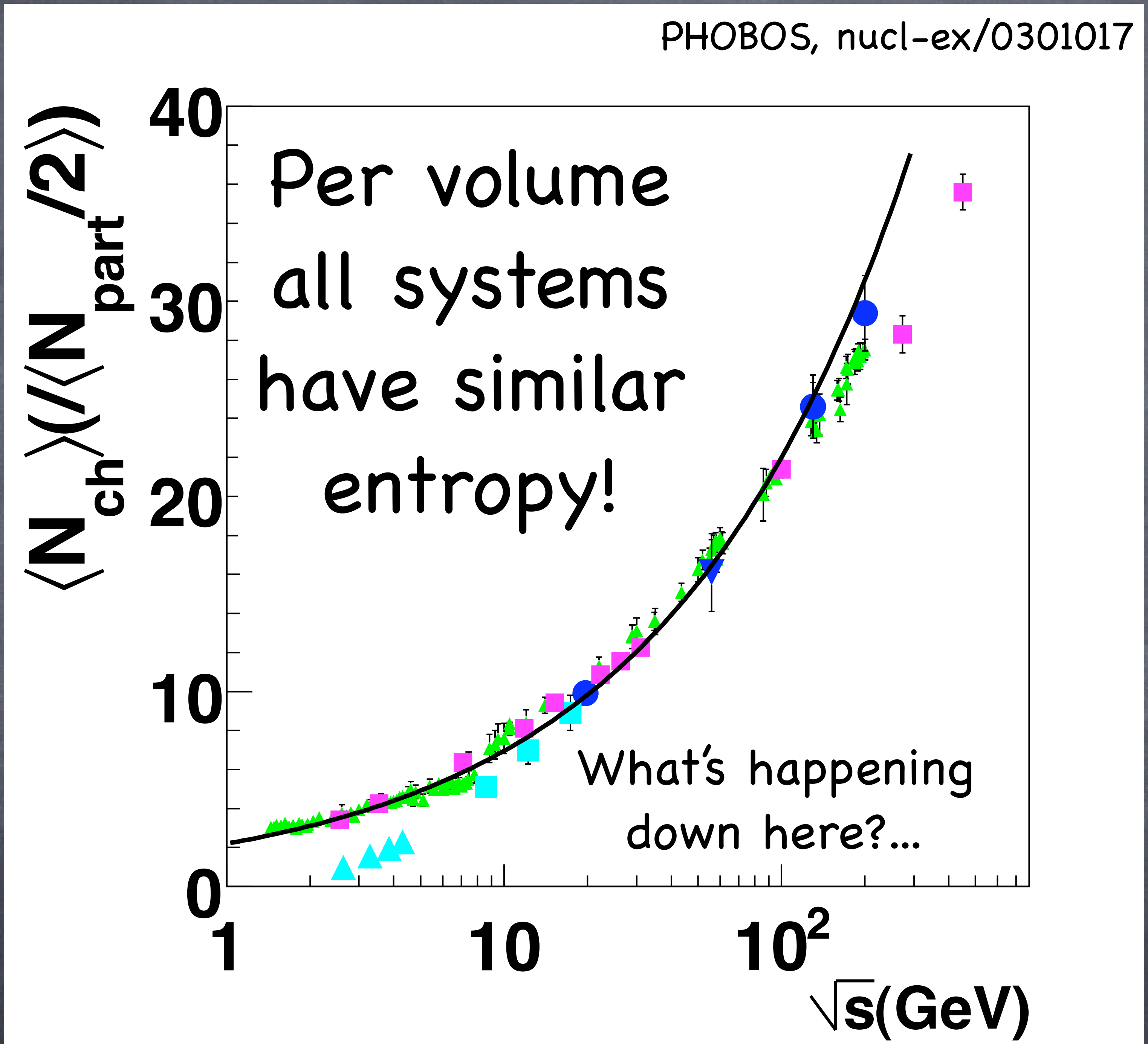




$$N_{ch} \propto V \propto N_{part} \propto A$$

Total multiplicity also scales with the volume determined by number of particpants

Total Multiplicity vs. Energy



A Little More Chemistry

In equilibrium:

$$G = E + PV - TS = \mu_B N_B$$

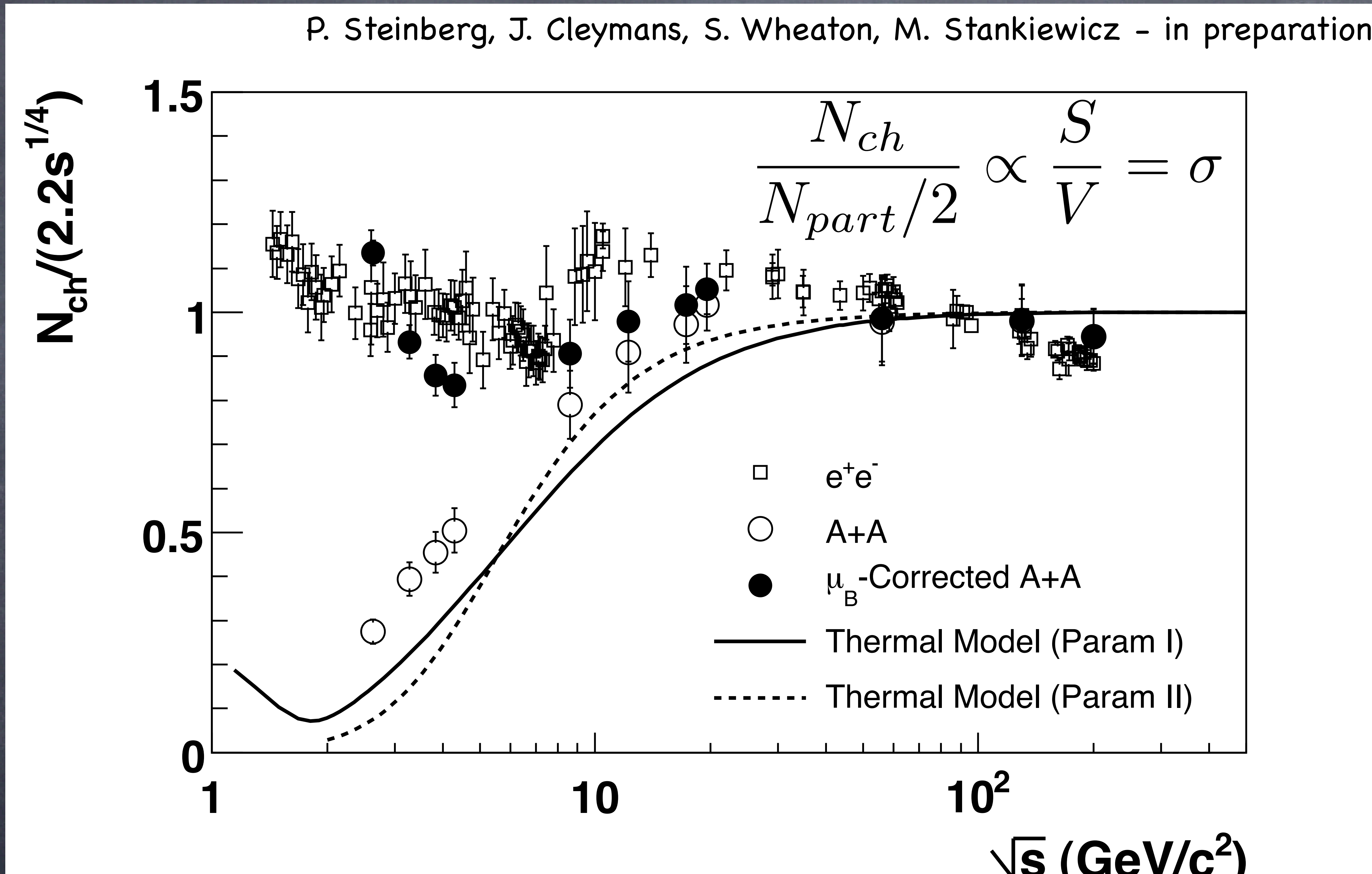
Rearranges to:

$$S = \frac{E + PV}{T} - \frac{\mu_B N_B}{T} = N_{part}$$

So chemical potential reduces multiplicity:

$$\Delta \frac{N_{ch}}{N_{part}/2} \propto \frac{\mu_B}{T}$$

Baryons Suppress Entropy



Either correct by $\Delta \frac{N_{ch}}{N_{part}/2} \propto \frac{\mu_B}{T}$ or just look at s/s_0

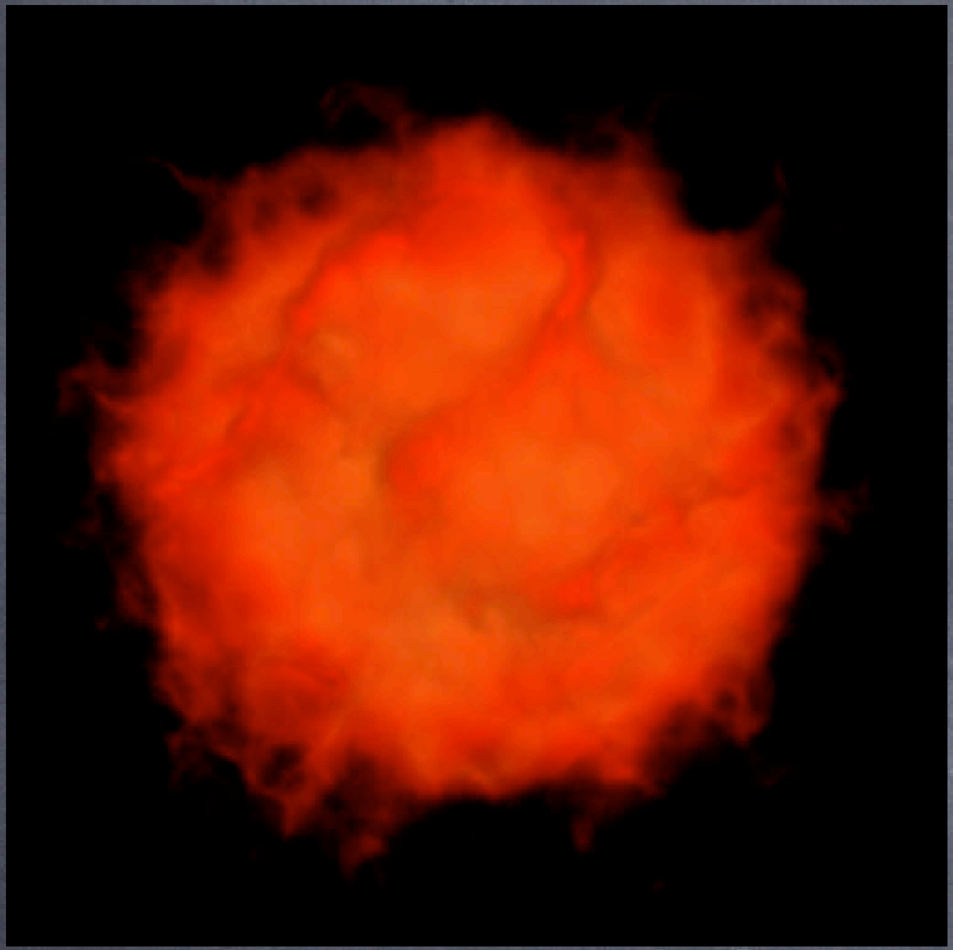
RHIC Thermochemistry

1. Temperature - hadronic blackbody
2. Entropy - determined by energy & geometry
3. Baryochemistry - suppresses entropy

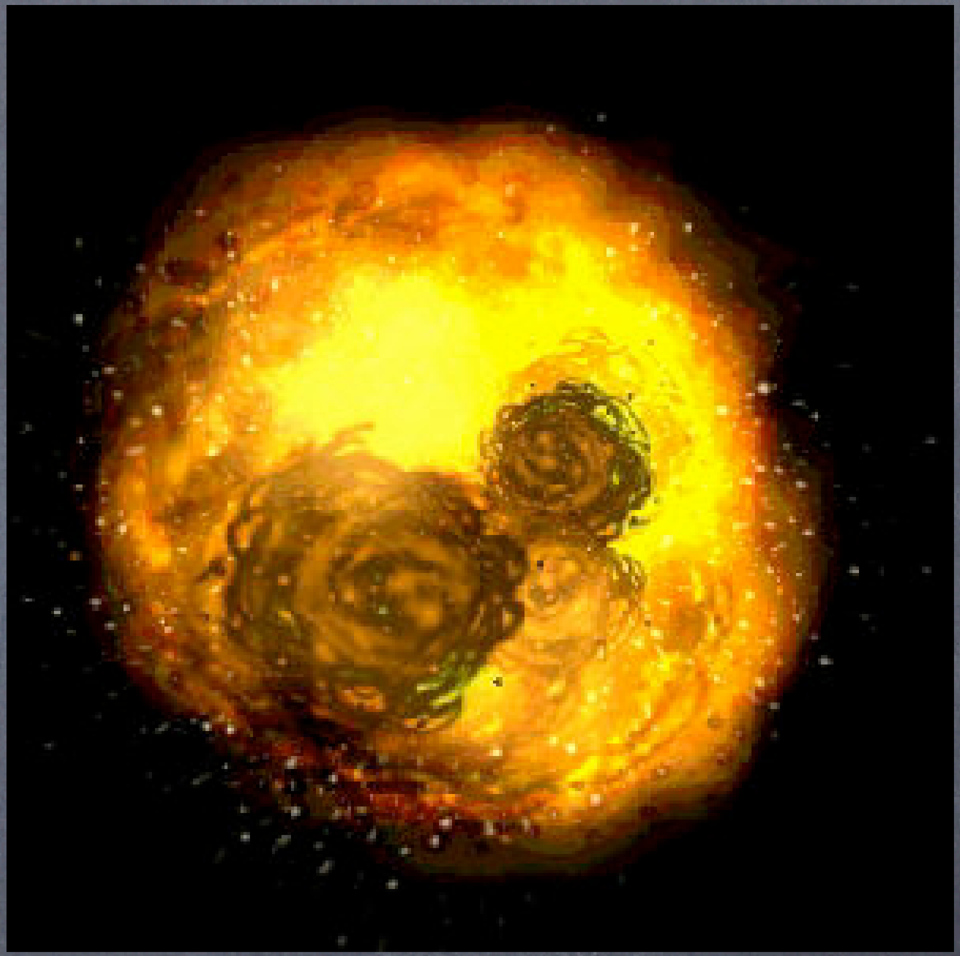
All of this is <u>descriptive</u> language, with no reference to dynamical mechanism

Also a static picture, with no mention of space-time evolution

RHIC Hydrodynamics

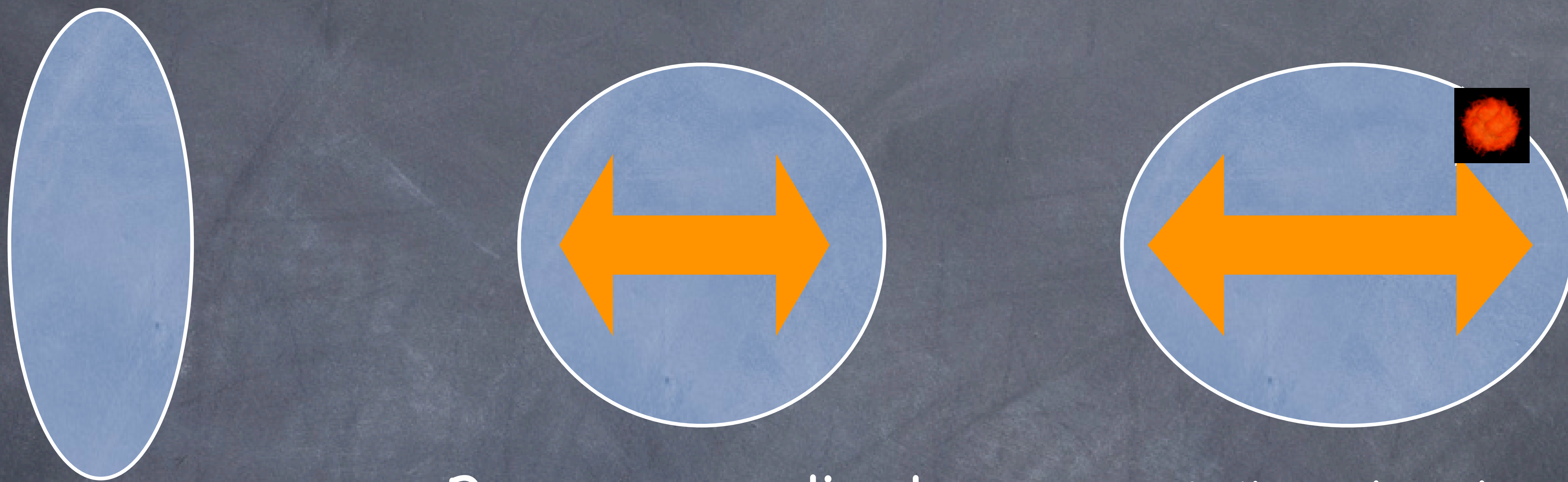


Is the system really
a “fireball”, just radiating
into free space?



Or is the system
more “explosive”, with
real dynamics preceding
the freezeout?

What is “Hydrodynamics”?



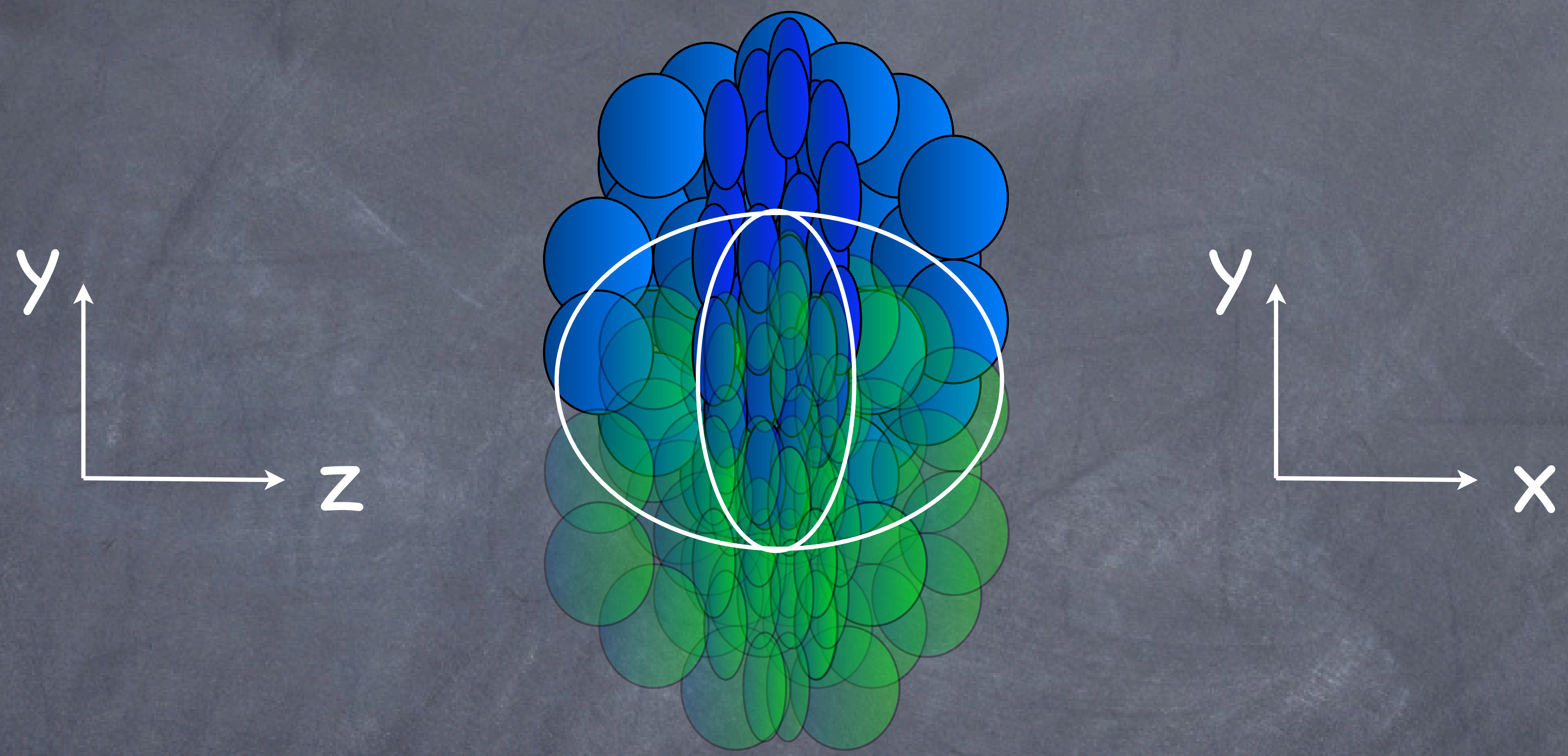
Energy density thermalized in a volume, adjacent cells are in causal contact

Presure gradients develop via expansion into vacuum

$$\partial_\mu T^{\mu\nu} = 0$$
$$P = \frac{\epsilon}{3}$$

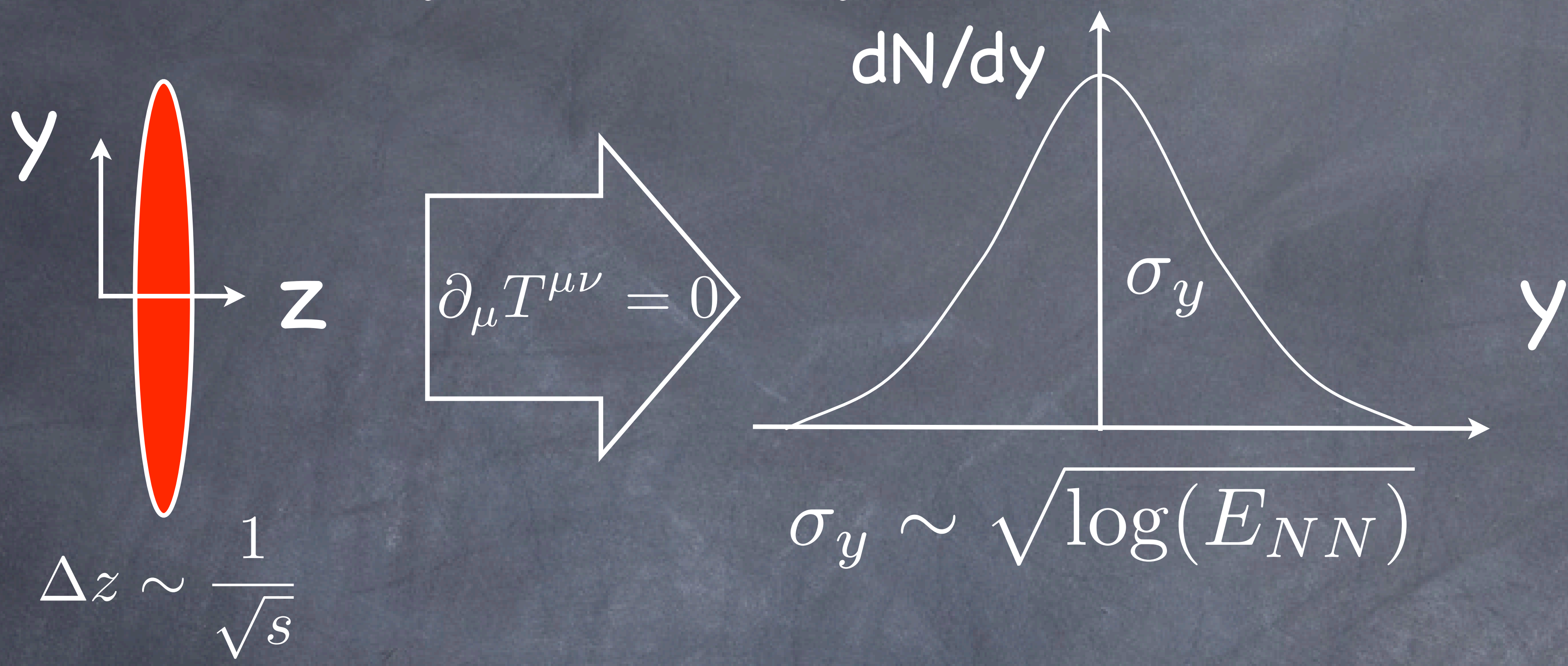
When local temperature is T_{ch} interactions turn off and fluid cells “freeze out” as isotropic fireballs (in fluid rest frame)

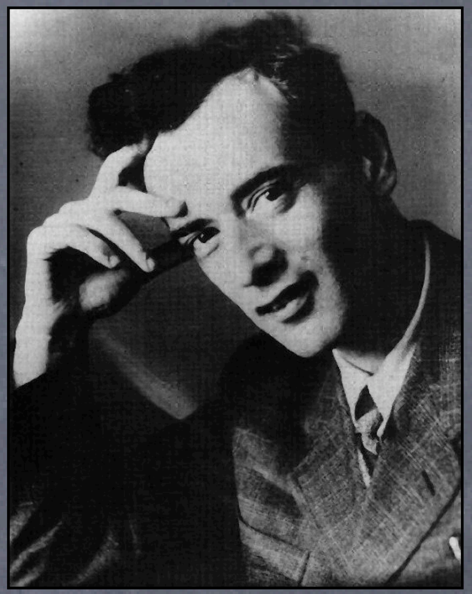
The Initial Conditions



1. Large compression in longitudinal direction
--> Longitudinal Flow
2. Almond shape in transverse plane
--> Radial & Elliptic Flow

2. Hydrodynamic Expansion

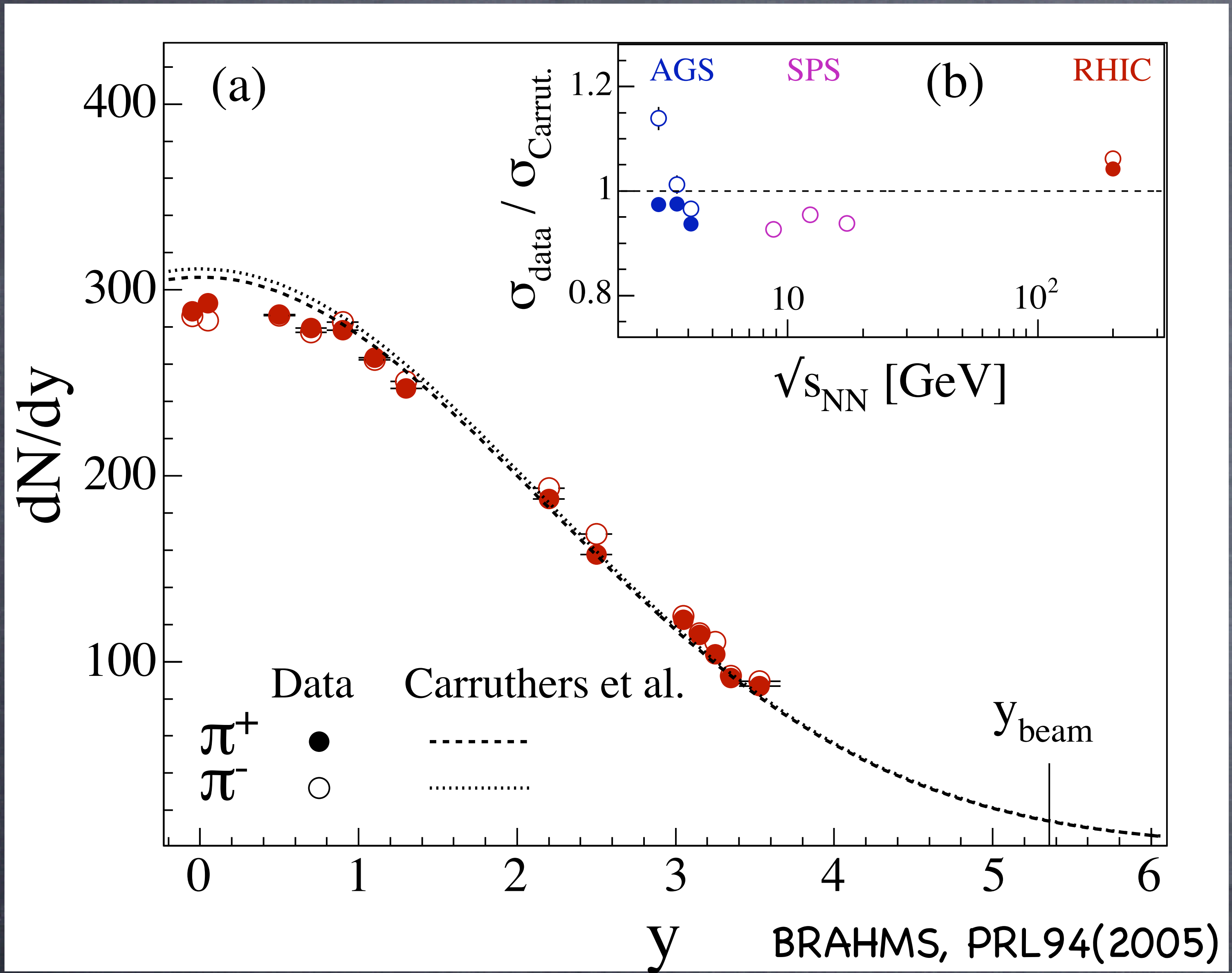


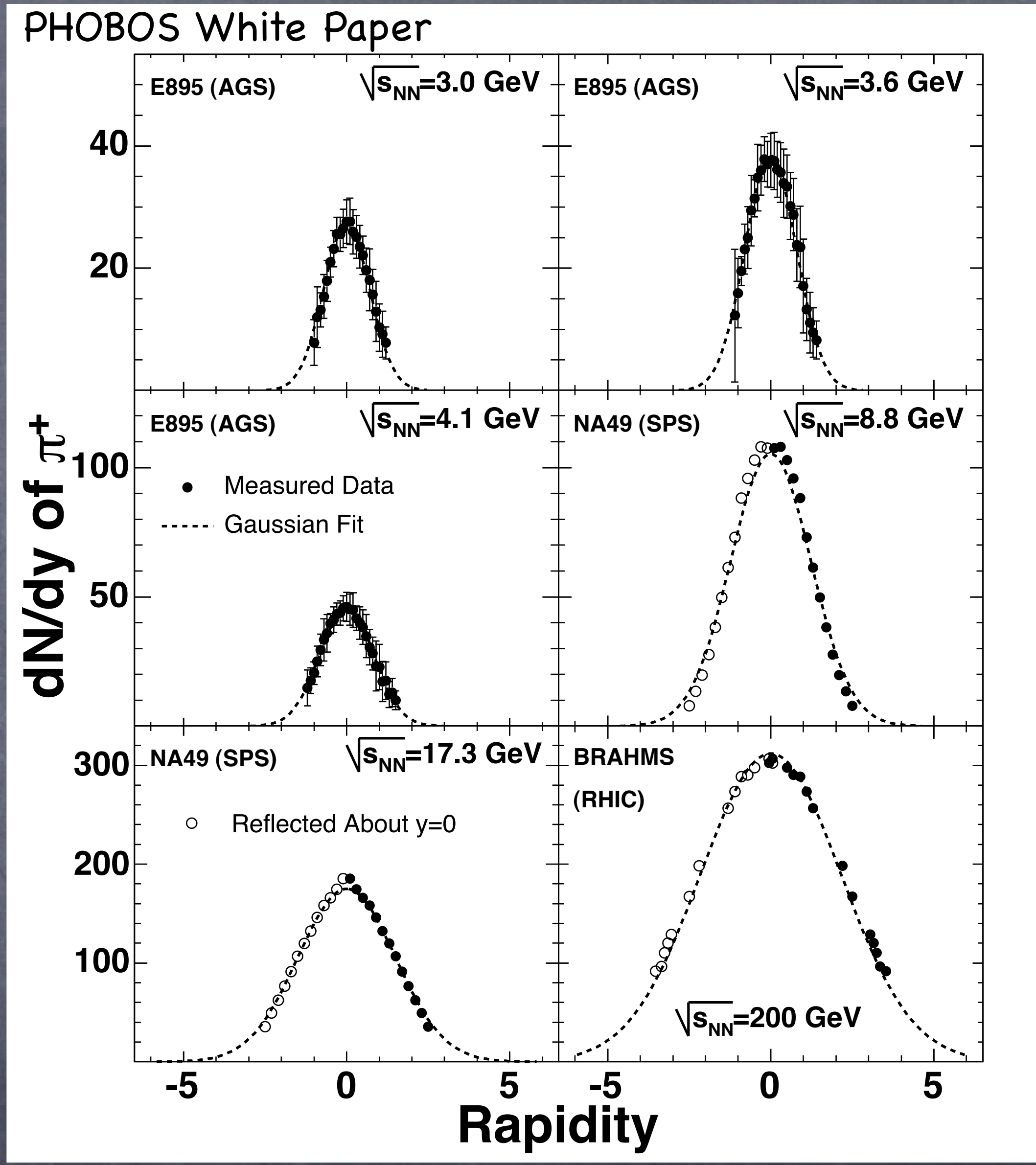


An important study of longitudinal dynamics was done in 1955, by Landau, using blackbody equation of state ($P=\epsilon/3$)

Hydrodynamics maps uniform slab in z into a Gaussian in rapidity.

Landau's Relevance in A+A





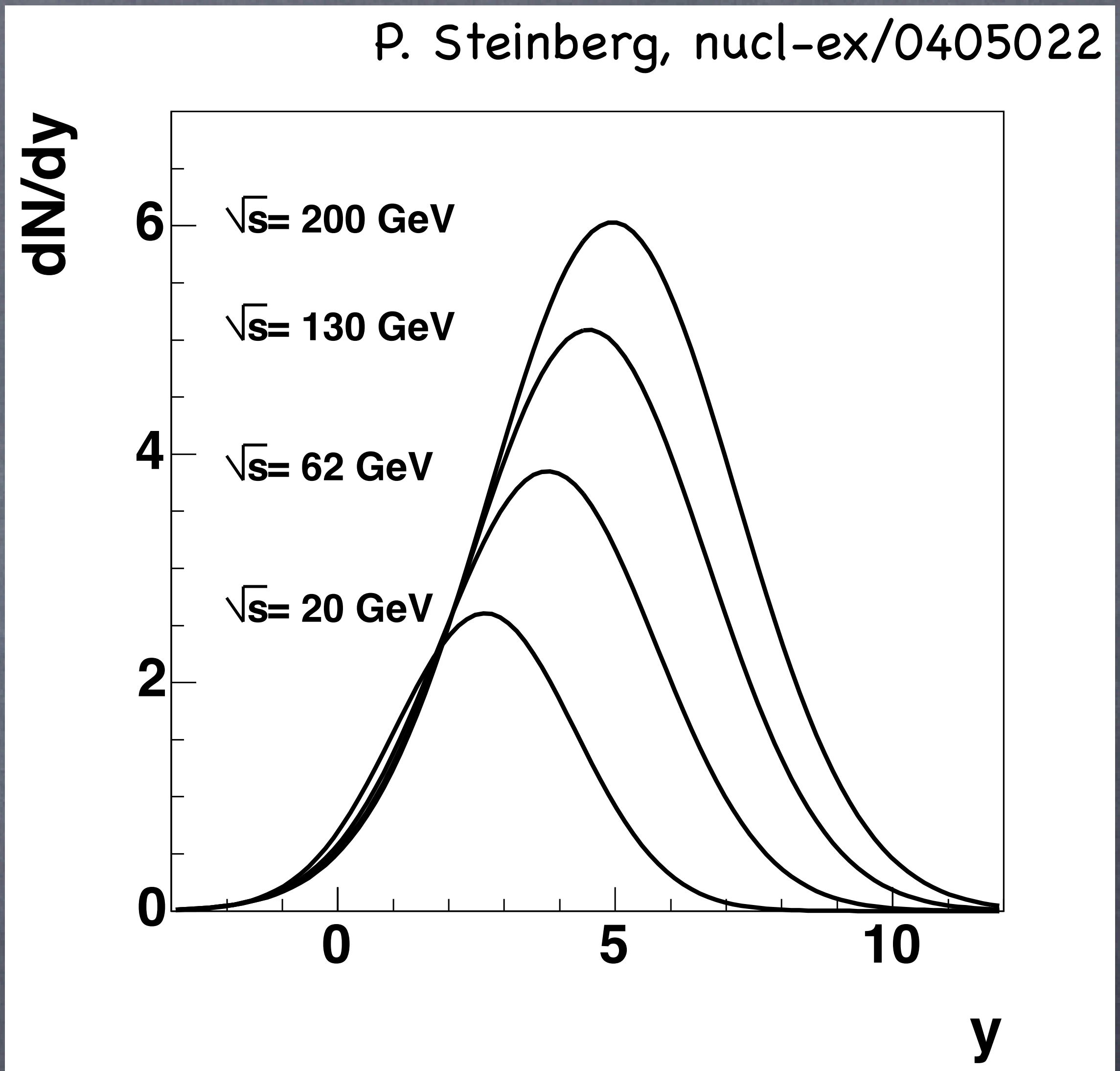
Gaussian formula works surprisingly well for pions

Longitudinal Scaling

$$\frac{dN}{dy} = K s^{1/4} \frac{1}{\sqrt{2\pi L}} \exp\left(-\frac{y^2}{2L}\right)$$

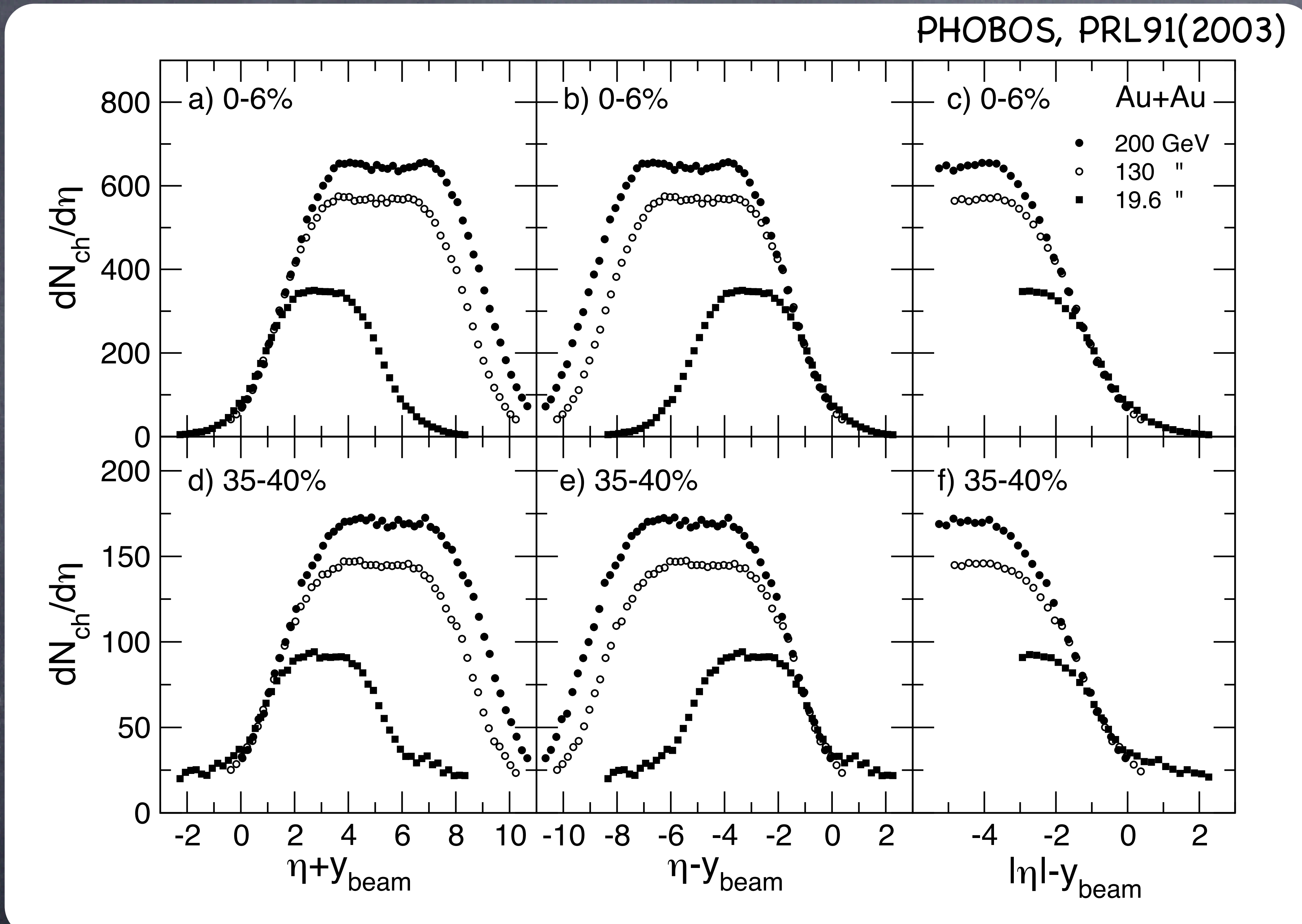
$$y' = y + y_{beam} = y + e^L$$

$$\frac{dN}{dy'} \sim \frac{1}{\sqrt{L}} \exp\left(-\frac{y'^2}{2L} - y'\right)$$



When observed in the rest frame of one of the projectiles ~invariance of particle yields!

"Longitudinal Scaling"



Central events

Peripheral events

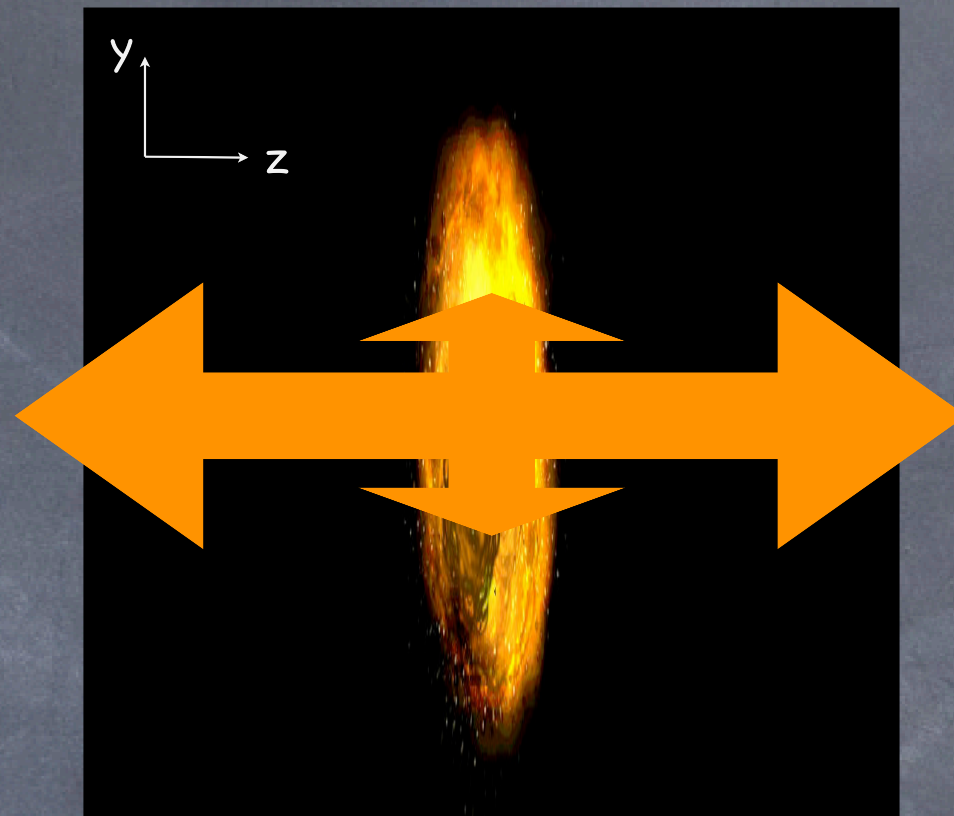
Rest frame of "target"

Rest frame of "projectile"

Reflected

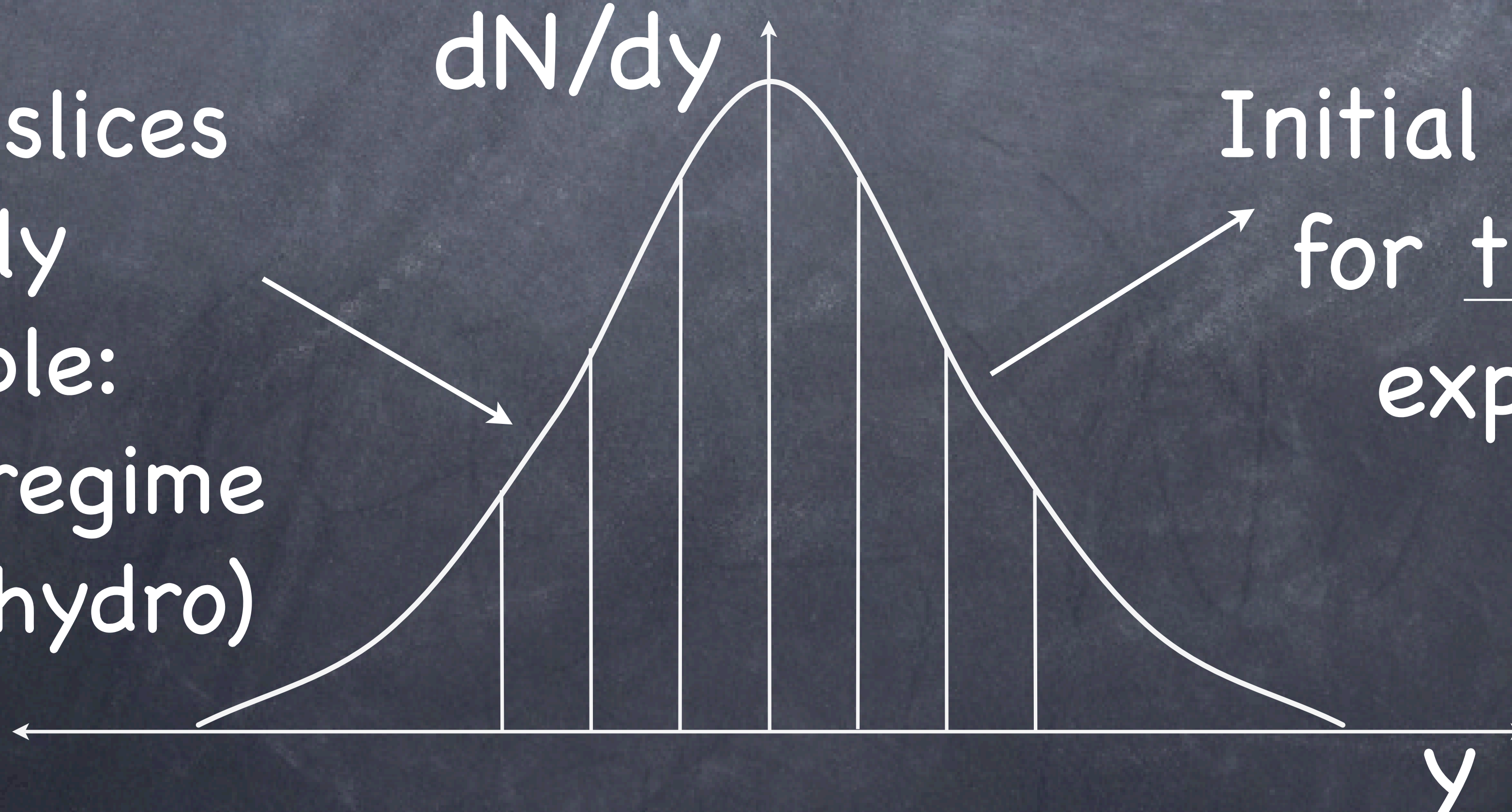
Longitudinal-->Transverse

Initial "explosion" along beam axis generates dN/dy, on time-scale of O(1/Δz)



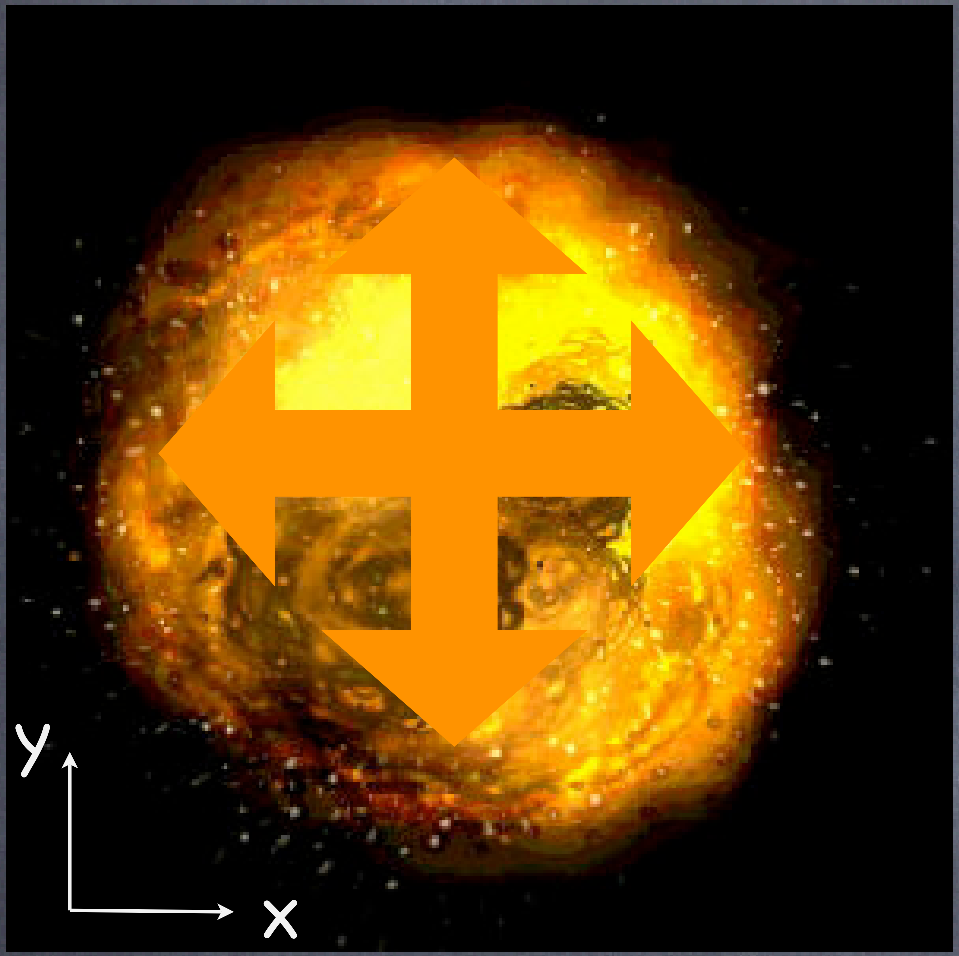
Transverse motion develops much slower, in times of O(1/R)

Rapidity slices quickly decouple: "scaling" regime (Bjorken hydro)

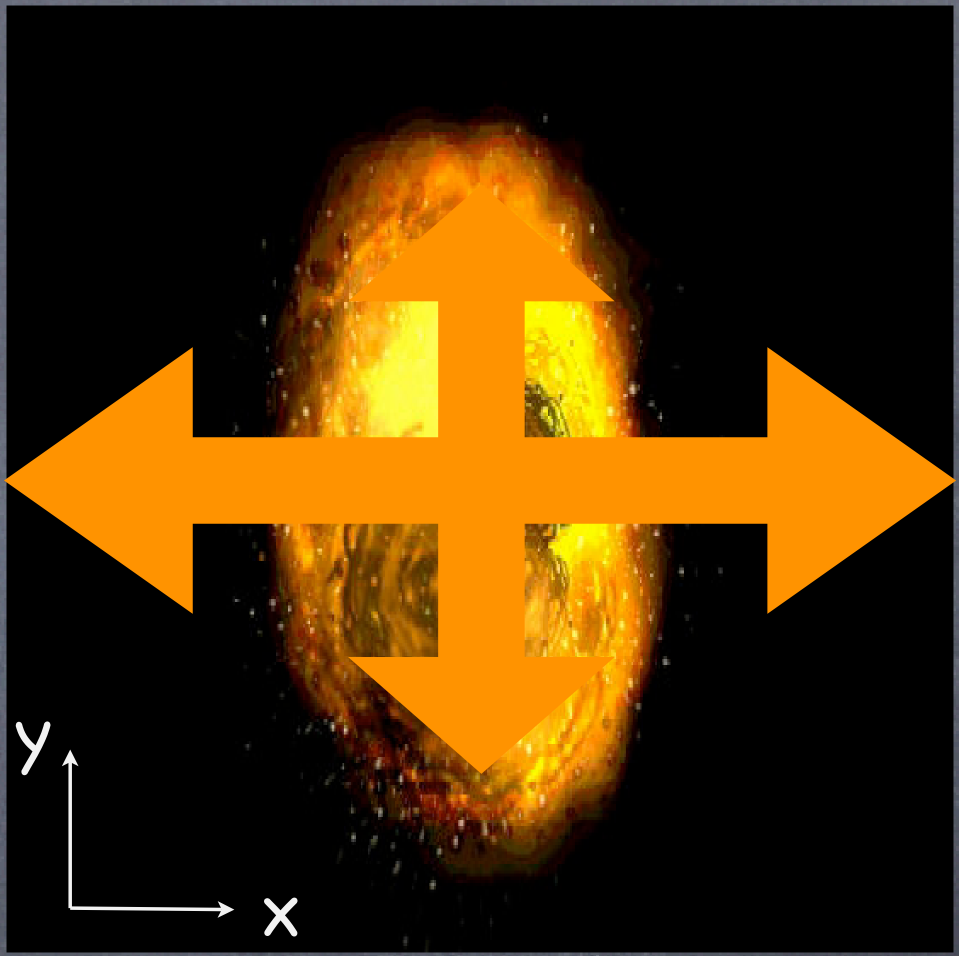


Initial conditions for tranverse expansion

Two Types of Transverse "Flow"

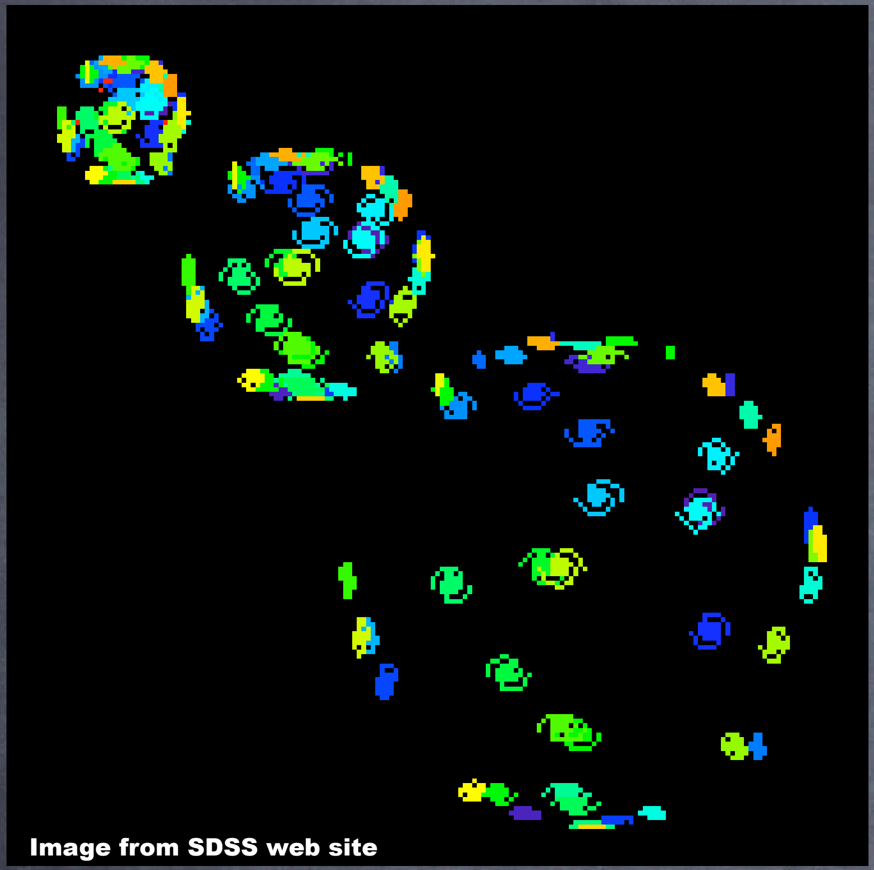


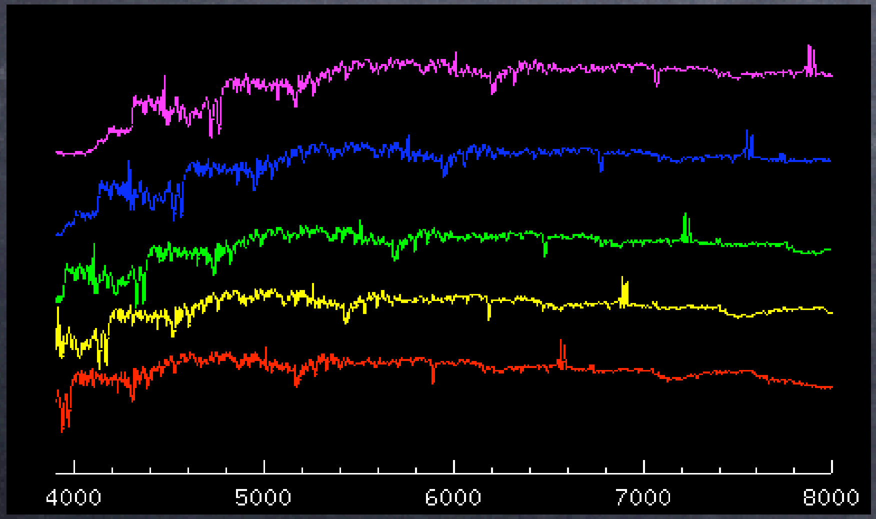
"Radial flow":
a collective push
outwards

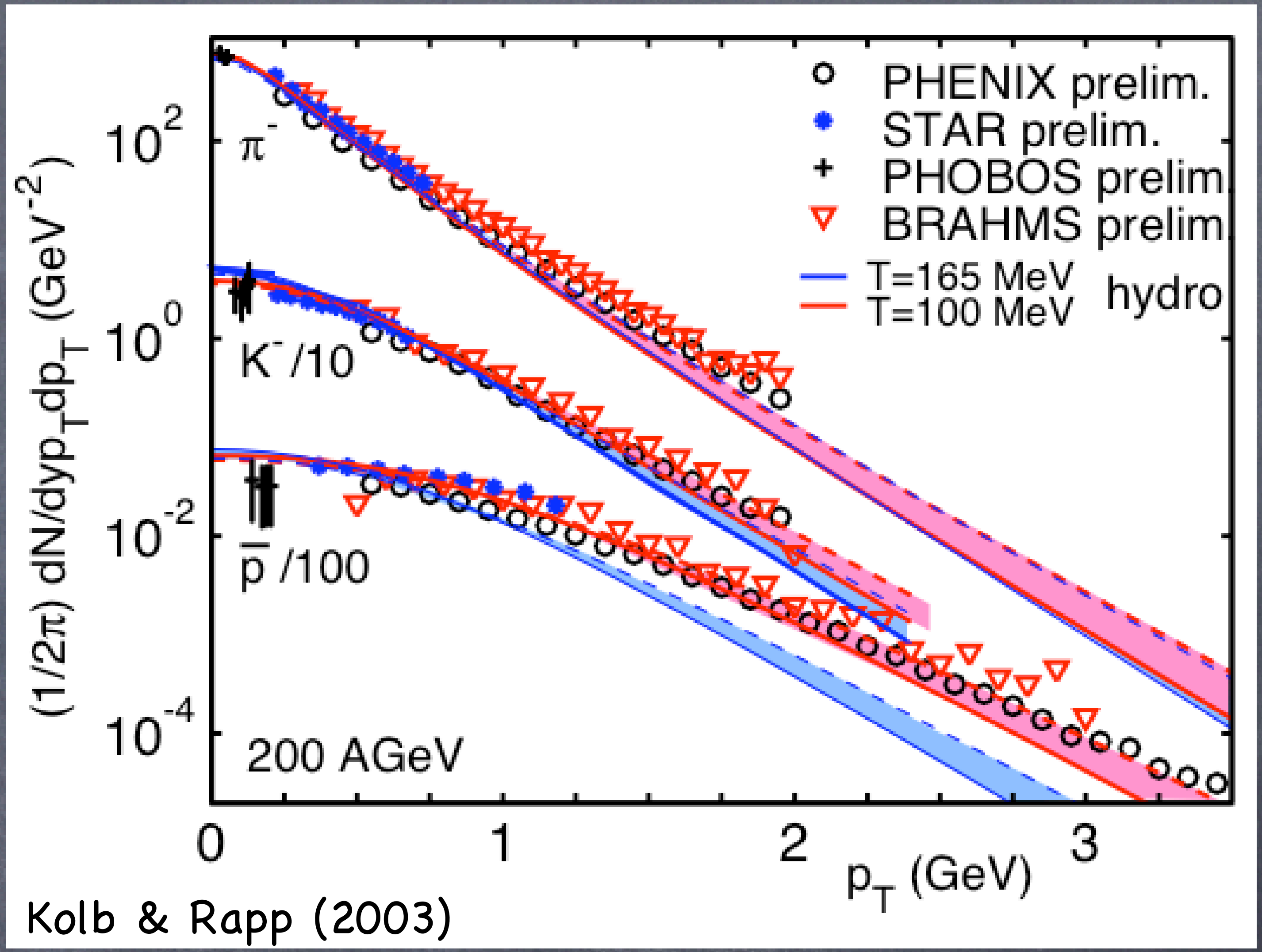


"Elliptic flow":
a collective push
along an axis

Blue-Shifted Spectra





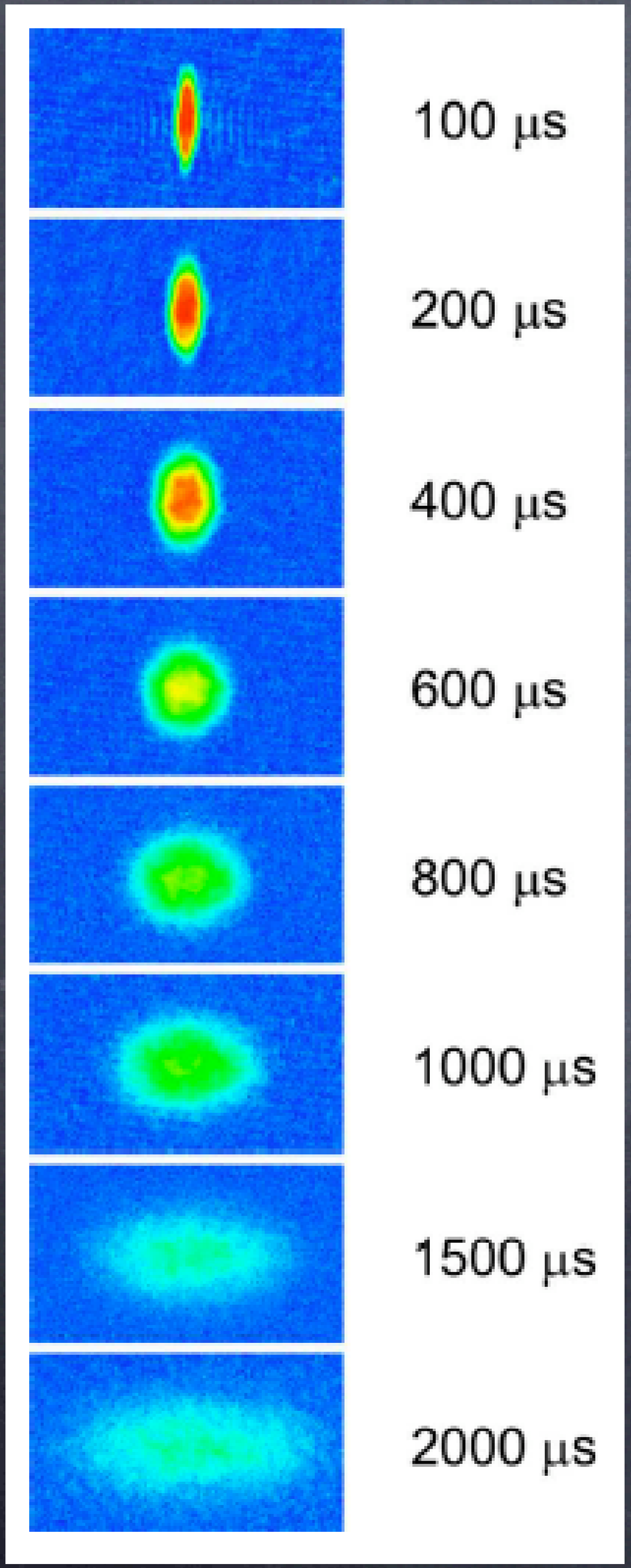


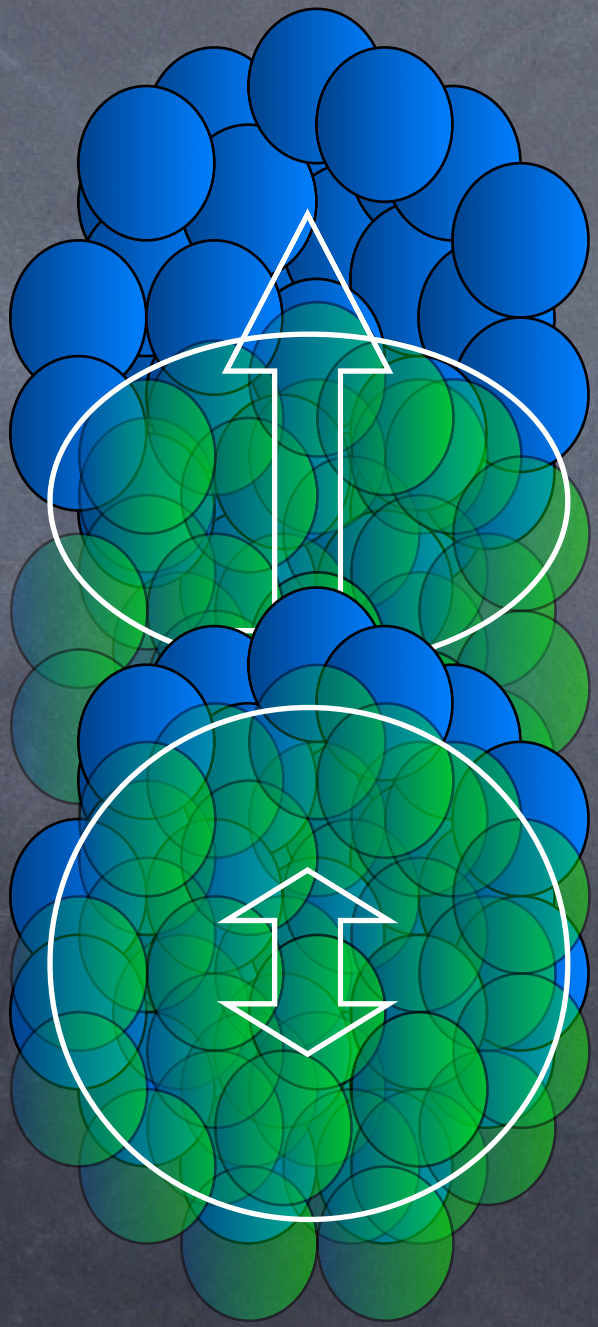
$$T_{eff} = T_0 + m\beta_T^2$$

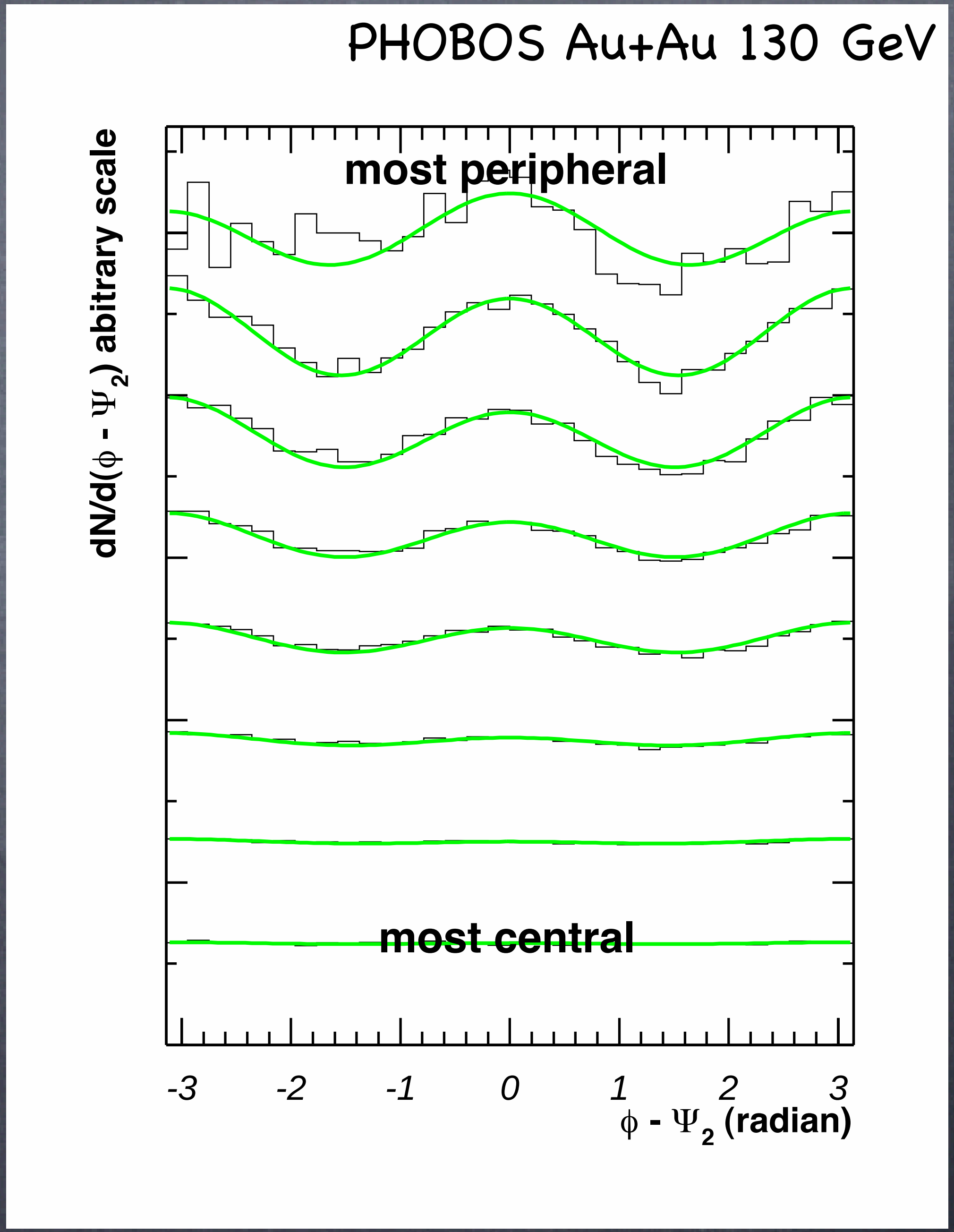
$$\langle \beta_T \rangle \sim .6$$

"Elliptic Flow"

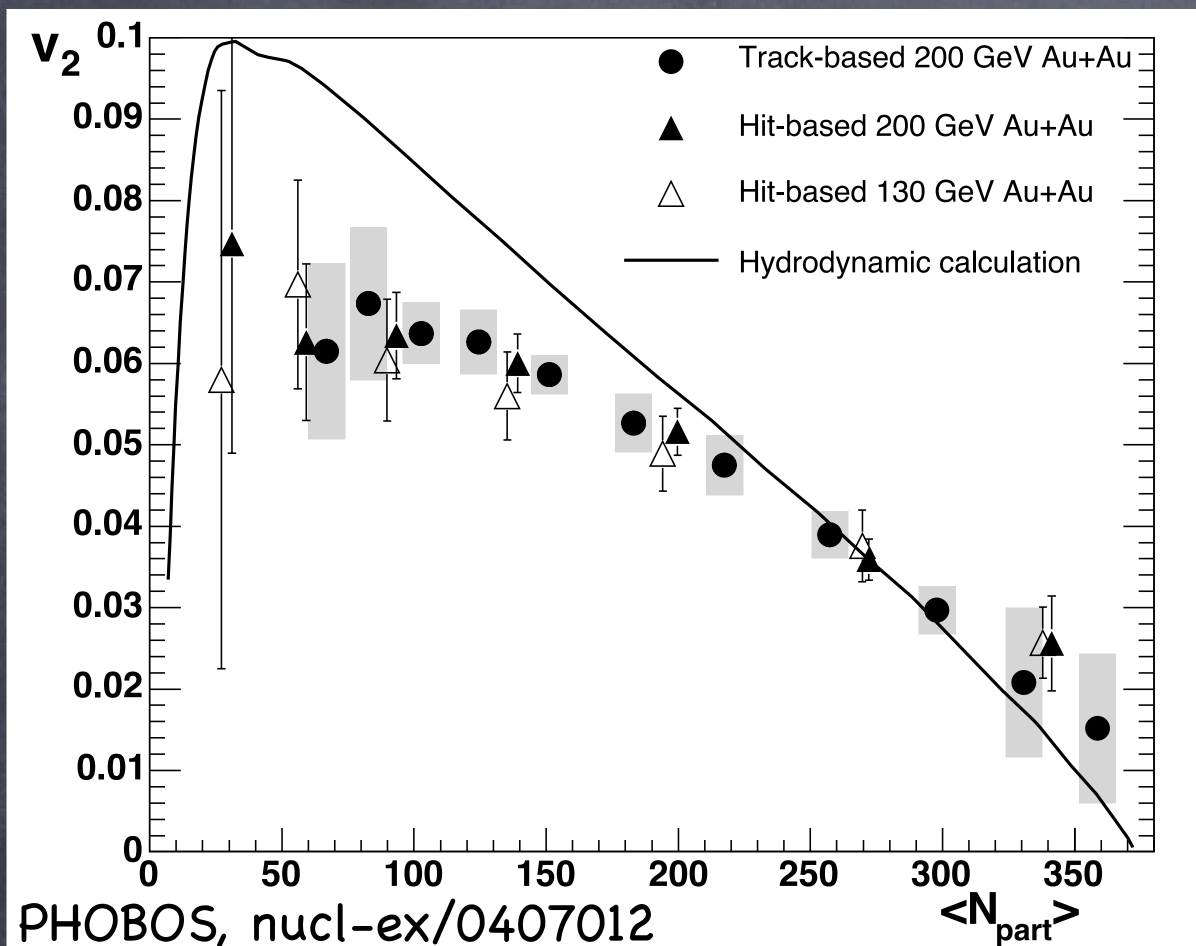
Strongly-coupled ^{6}Li atoms in a magnetic trap at the Feshbach resonance (O'Hara et al, 2003)

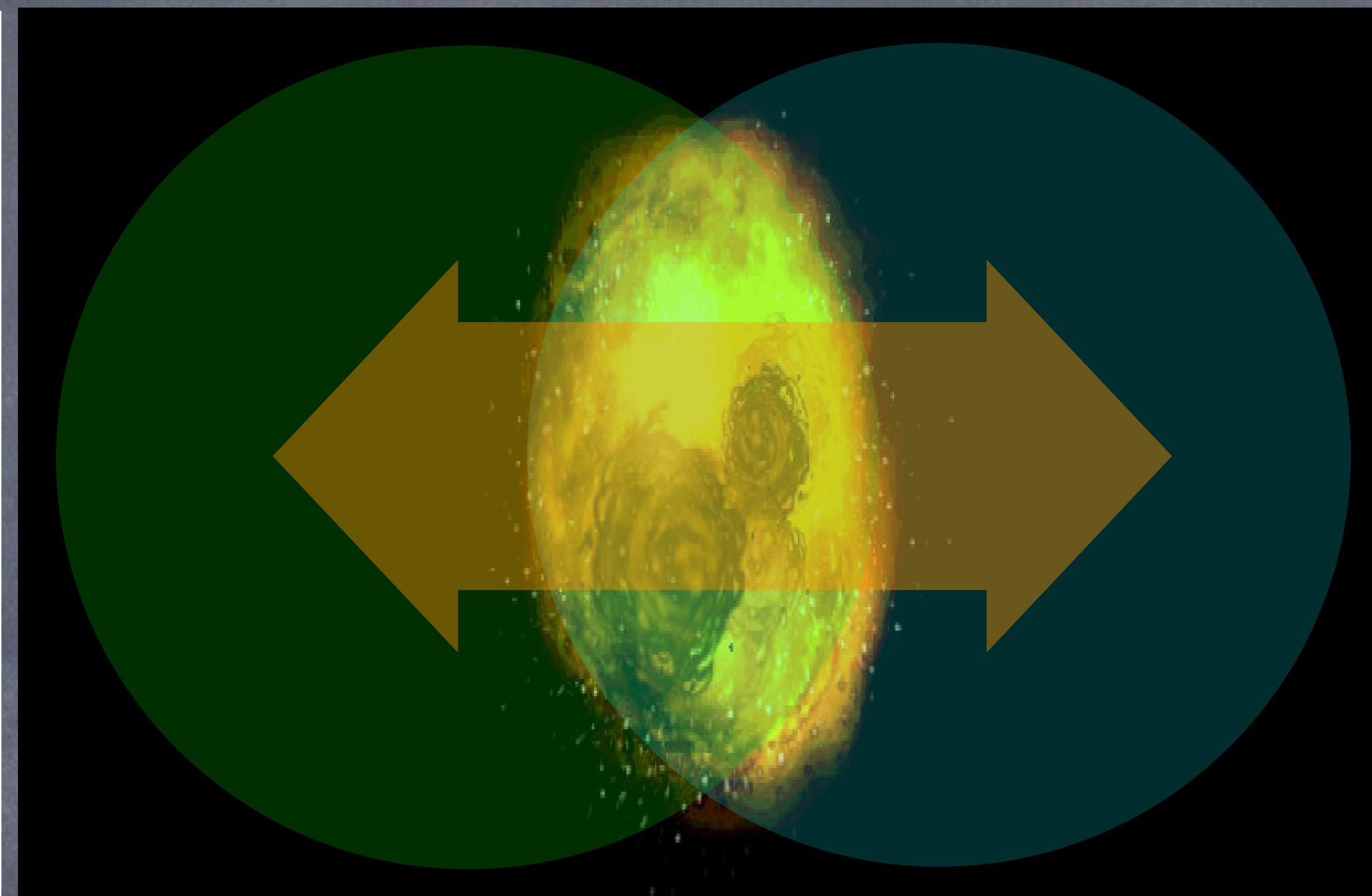






Elliptic Flow Follows Hydro





$$\frac{1}{N}\frac{dN}{d\phi} = 1 + 2v_1\cos(\phi - \Phi_R) + 2v_2\cos(2[\phi - \Phi_R]) + \ldots$$

Fourier decomposition can be compared with hydrodynamical calculations with τ_{th}~0.6fm/c

RHIC Hydrodynamics

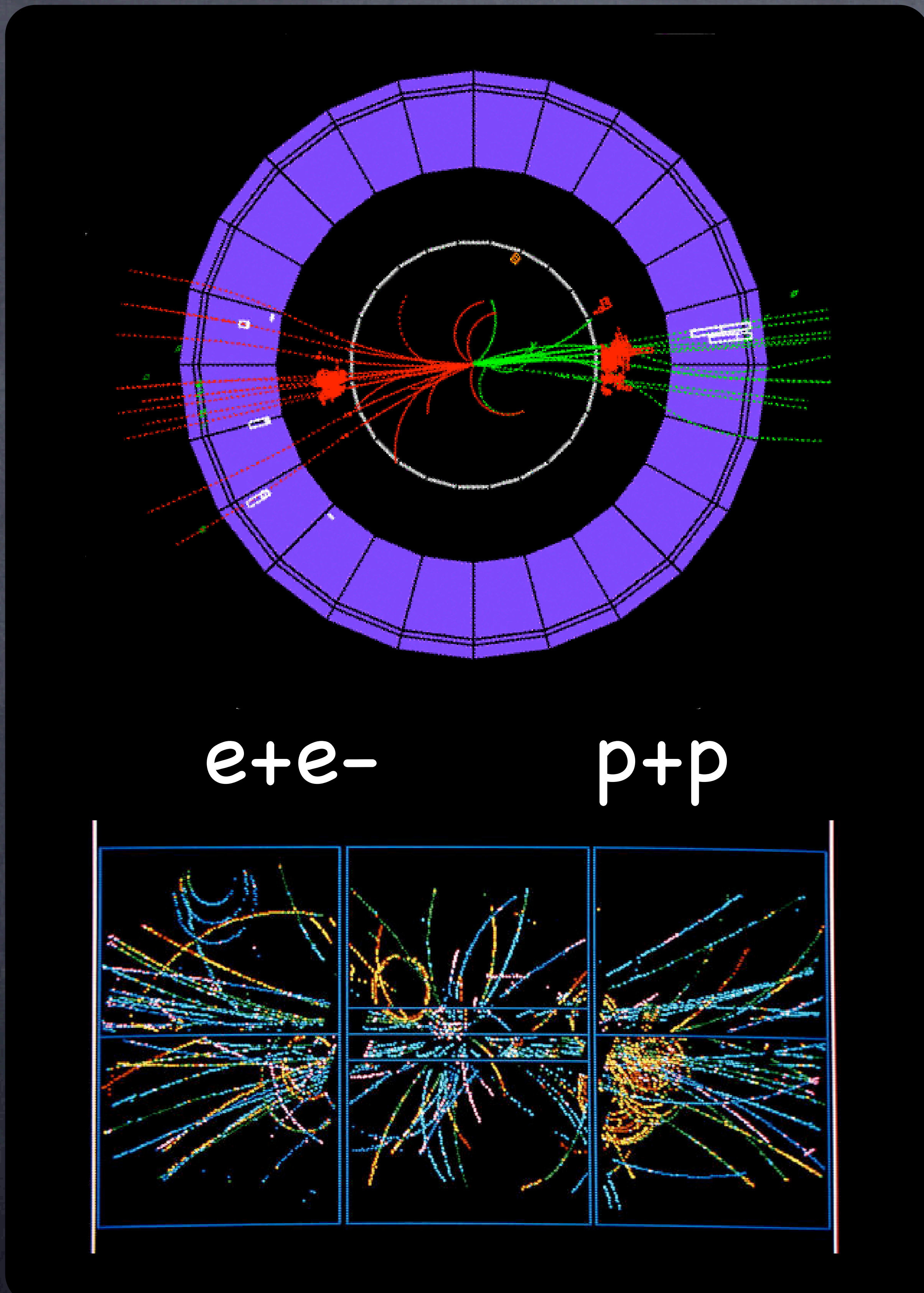
1. Initial collision defines energy (entropy) and volume, as well as its shape

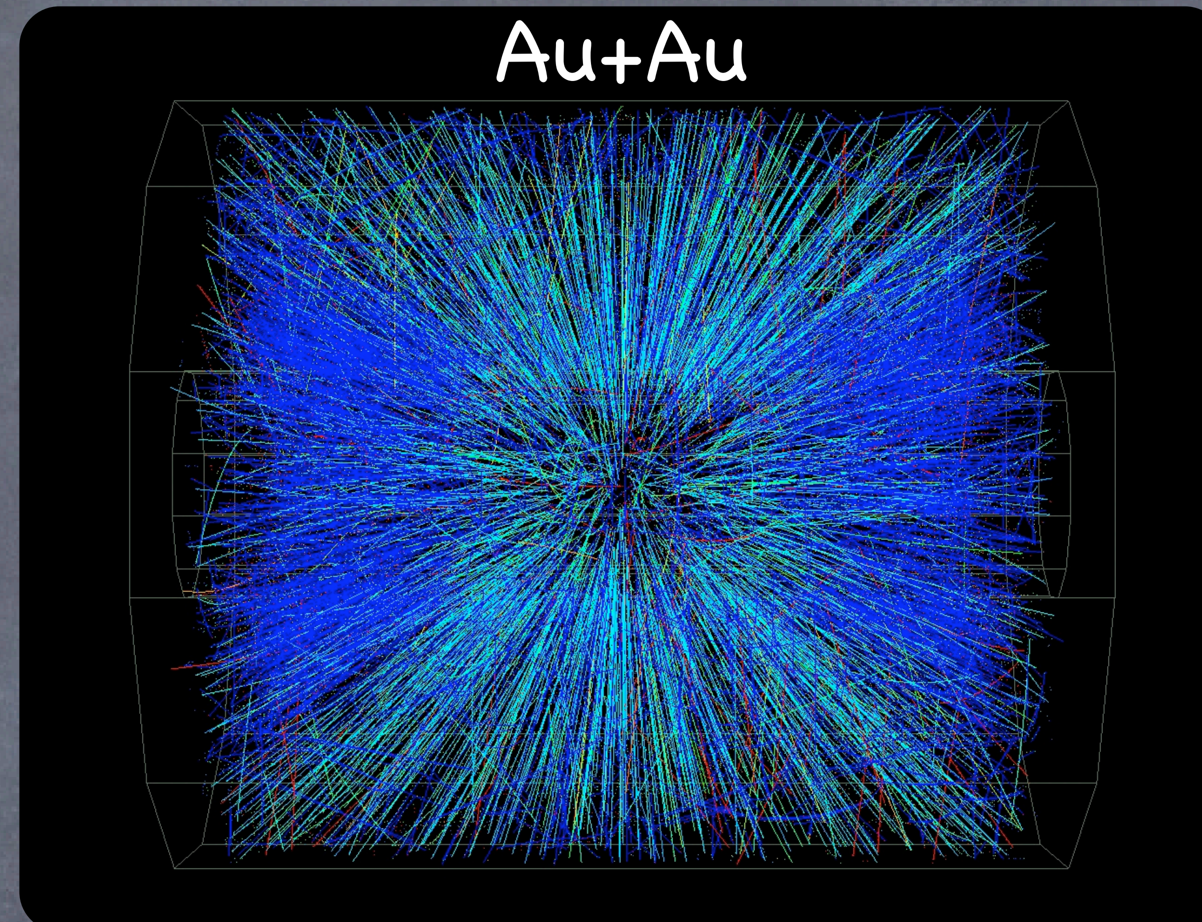
2. Longitudinal distributions described approximately by Landau's hydro, implying $\tau_{th} << 1$ fm/c and an energy density of 4 TeV/fm^3

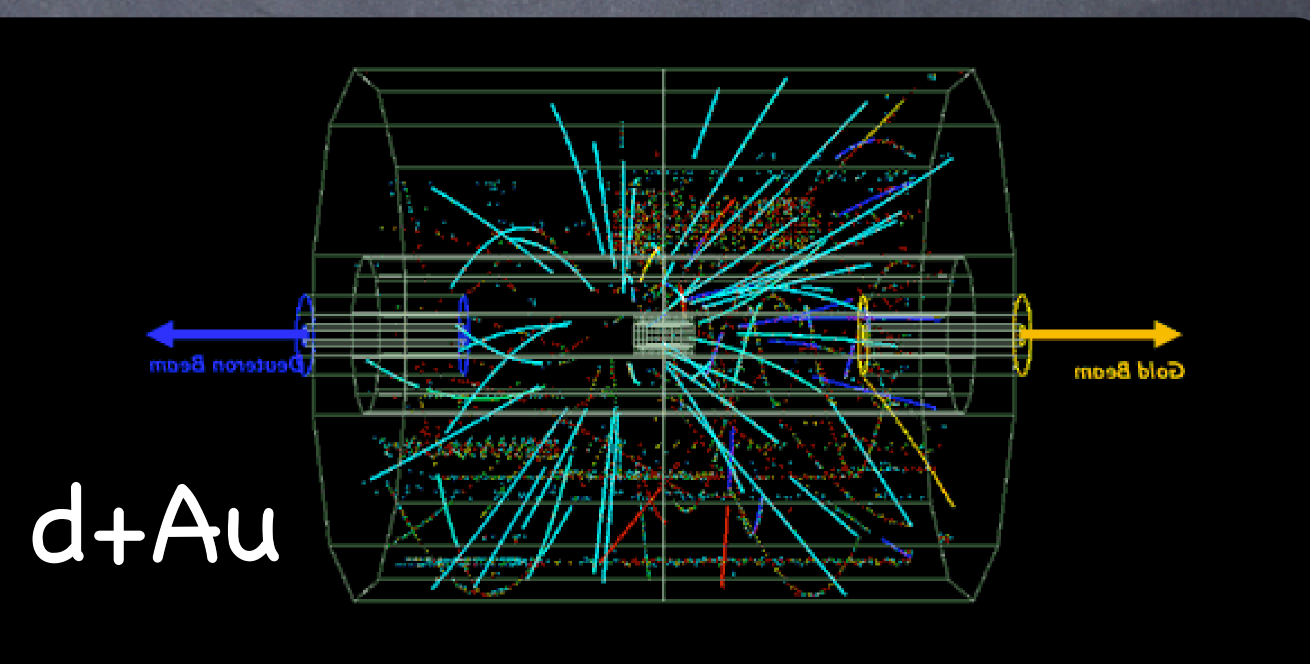
3. Transverse pressure described by hydro, starting at a later time $\tau_{th} \sim 0.6$ fm/c and energy density of ~30 GeV/fm^3

All of this would be "crazy" if it didn't work

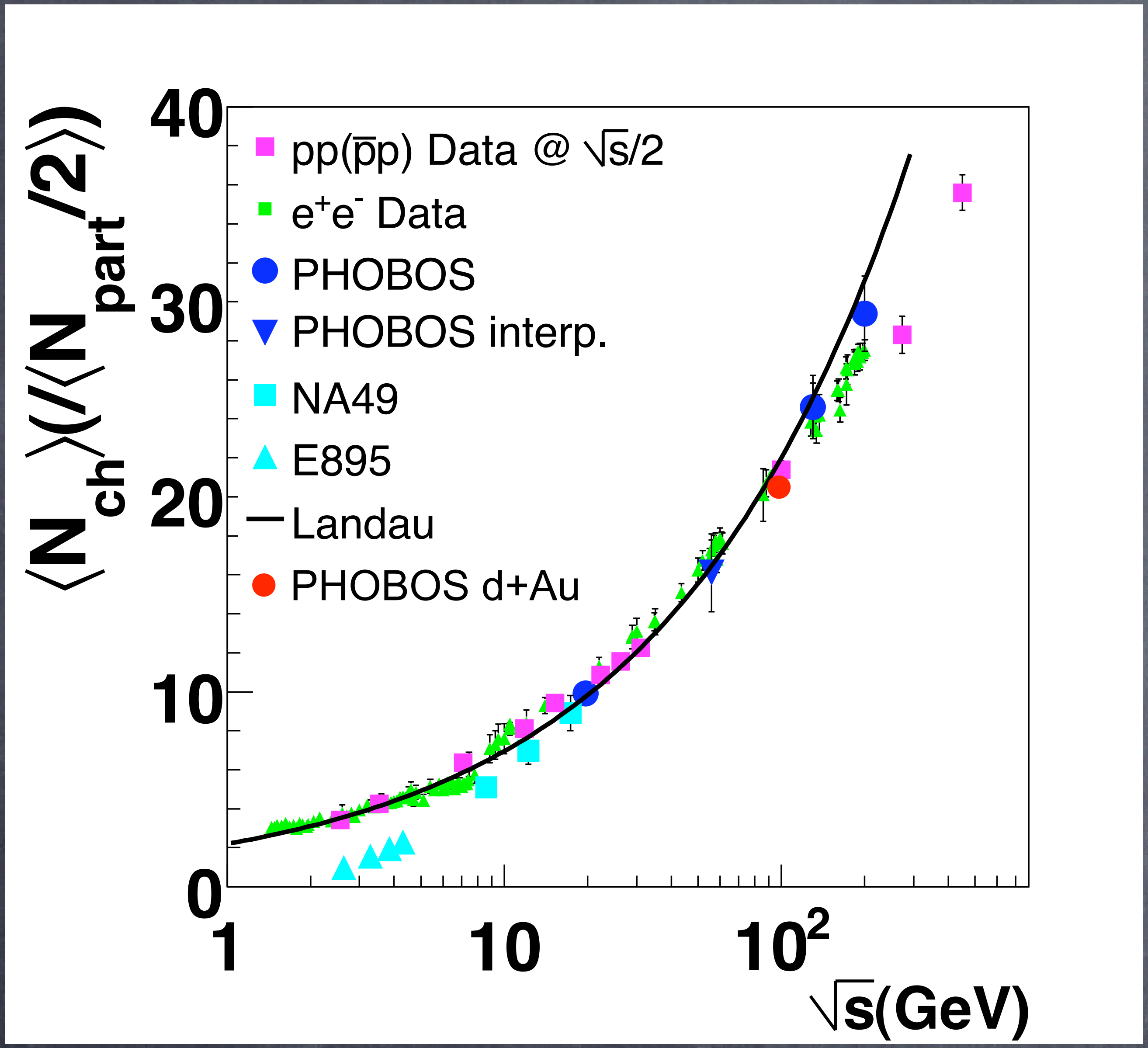
Can we turn hydro "off"?

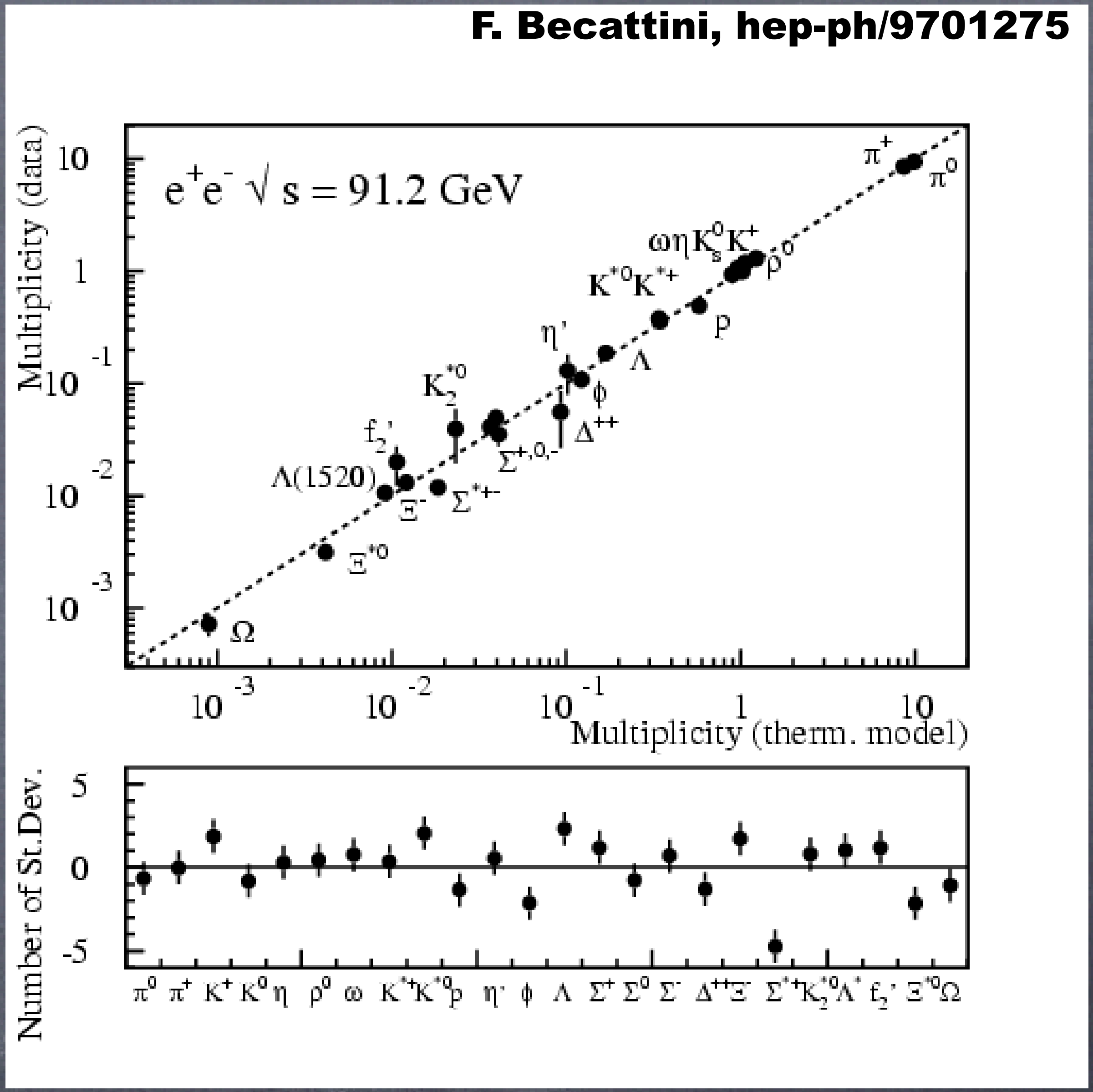




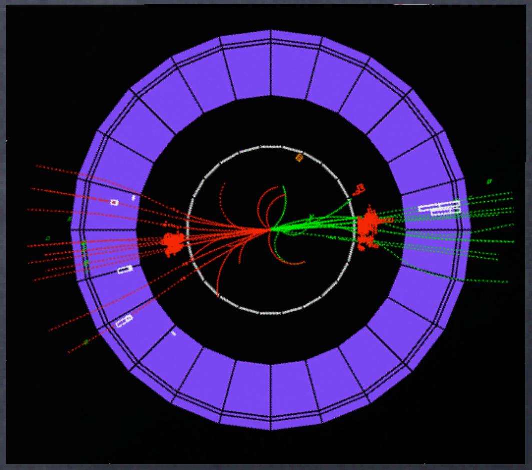


Thermalization

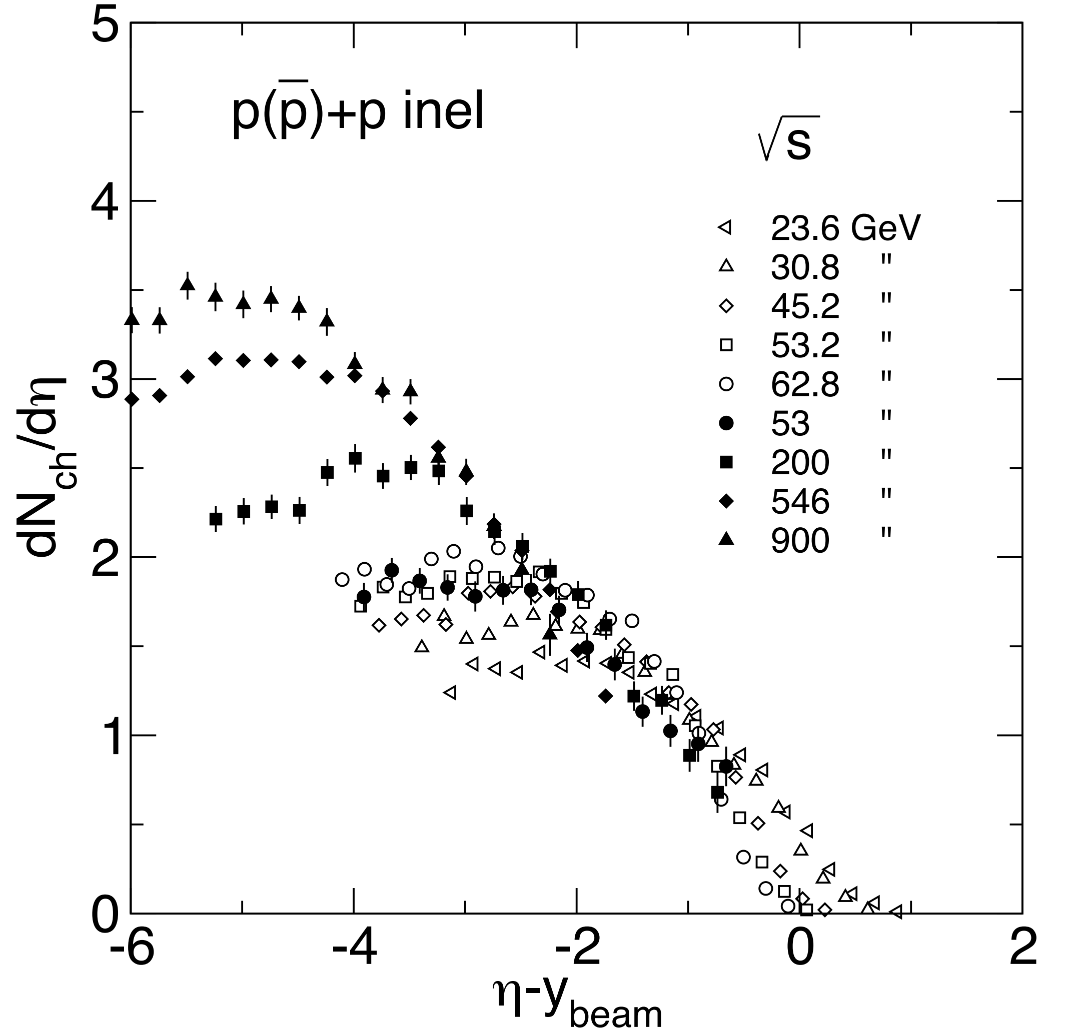


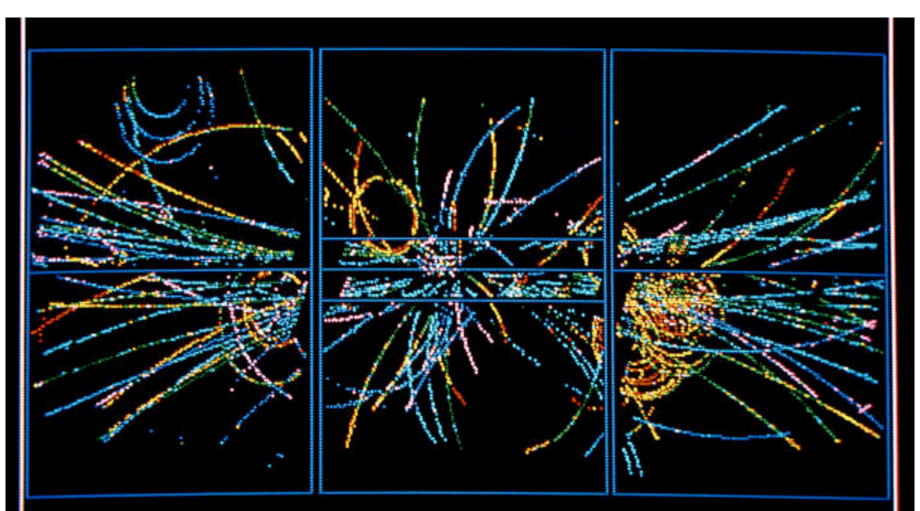


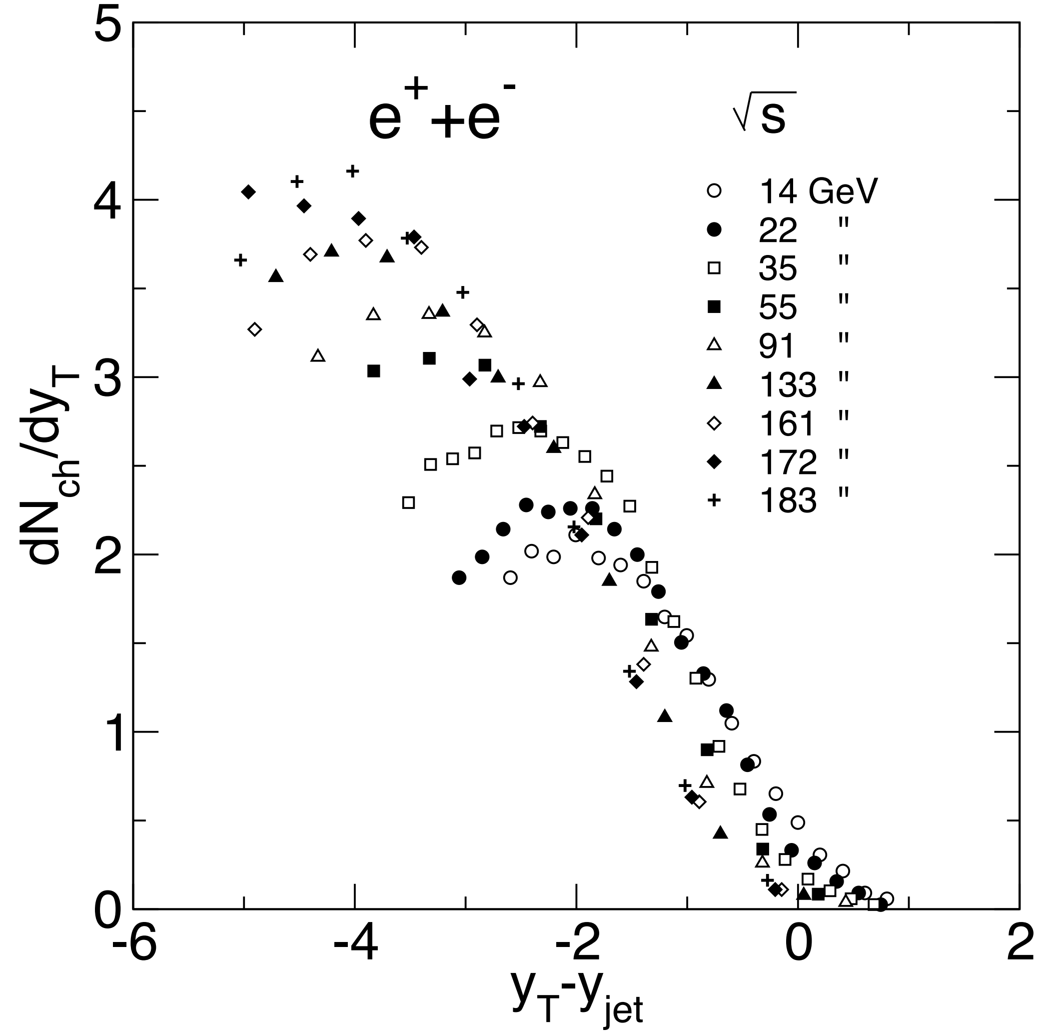
Even e+e- annihilations emit hadrons as a blackbody w/ $T \sim 160 MeV$.

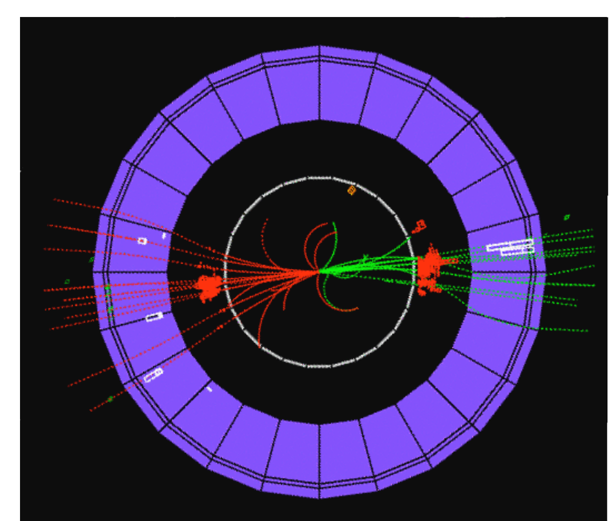


Longitudinal Dynamics

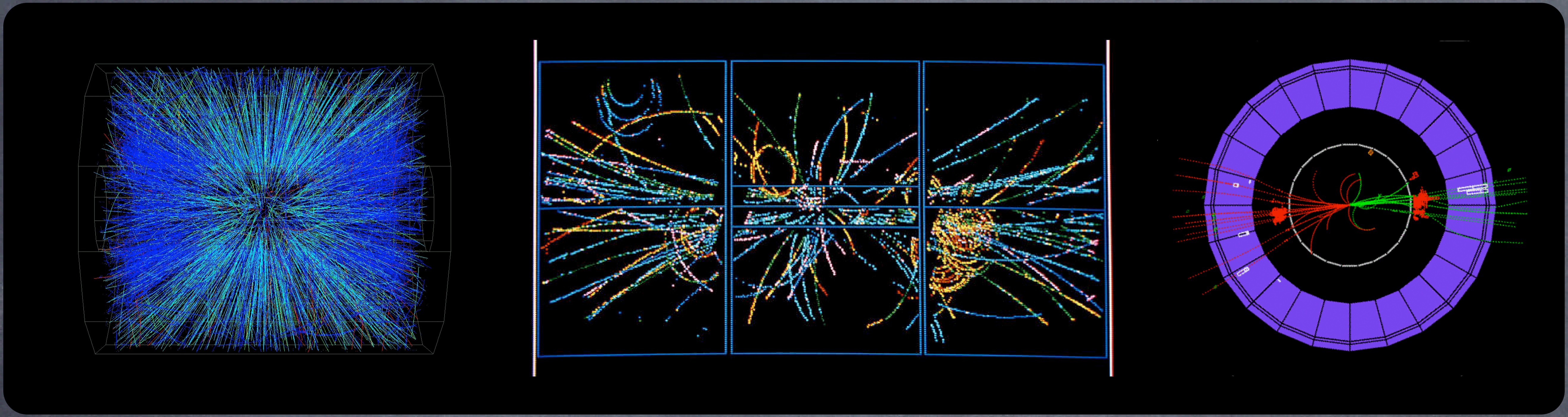








A Conjecture



Perhaps the interactions are so strong and so fast in the very early stages of strong interactions that <u>all</u> reactions start as the "near-ideal" fluid?

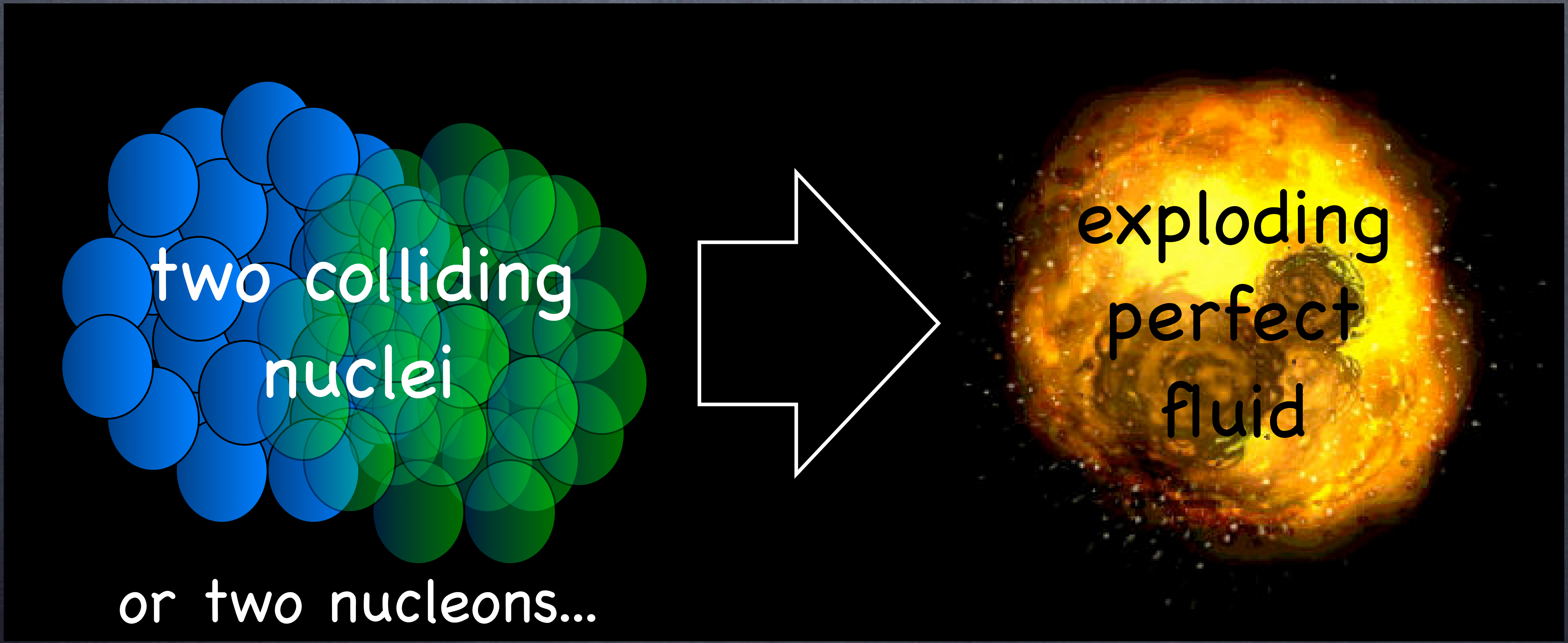
Bulk features will be similar, but details should differ

Not an original idea, but becomes more compelling with higher-quality data from RHIC p+p, d+A, A+A

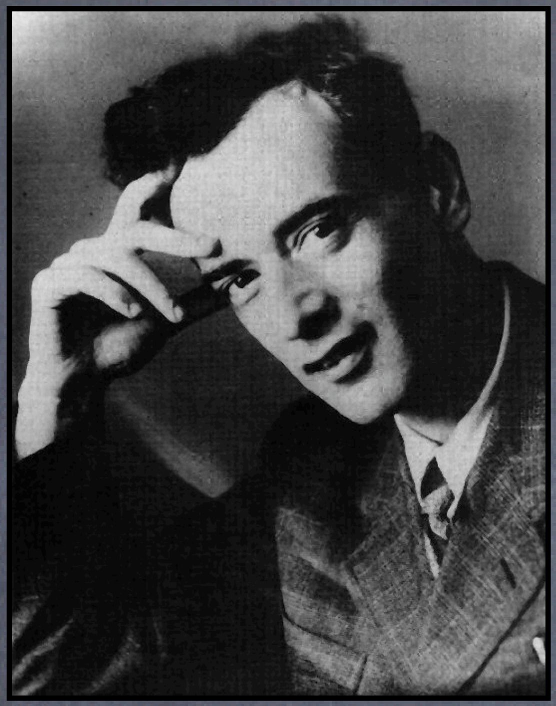
The Big Mystery

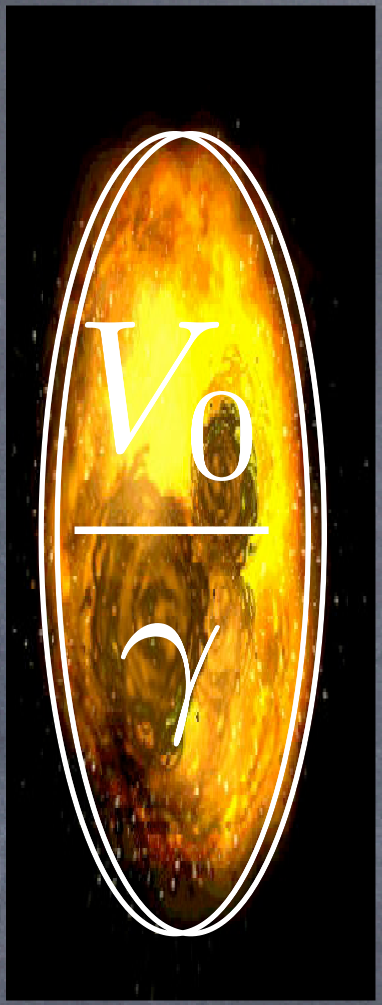
From this point of view, strong interactions don't look so complicated (modulo details influenced by hard-scattering of partons)

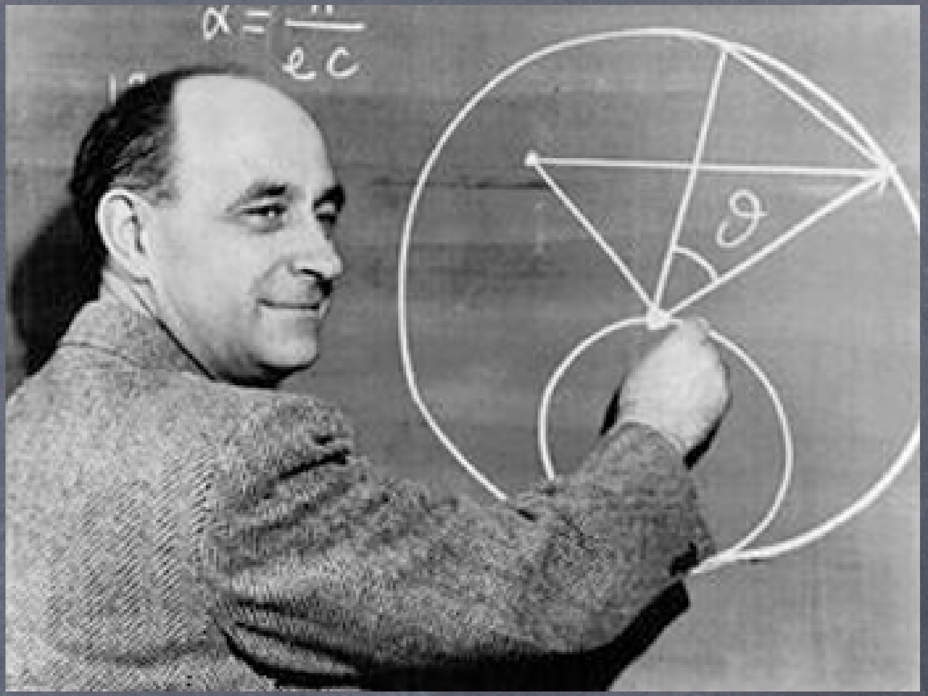
But how exactly do we get from



Landau & Fermi







Assume <u>nothing</u> about dynamics or degrees of freedom except they rapidly and efficiently thermalize <u>all of the energy</u> in this <u>volume</u>

Degrees of Freedom

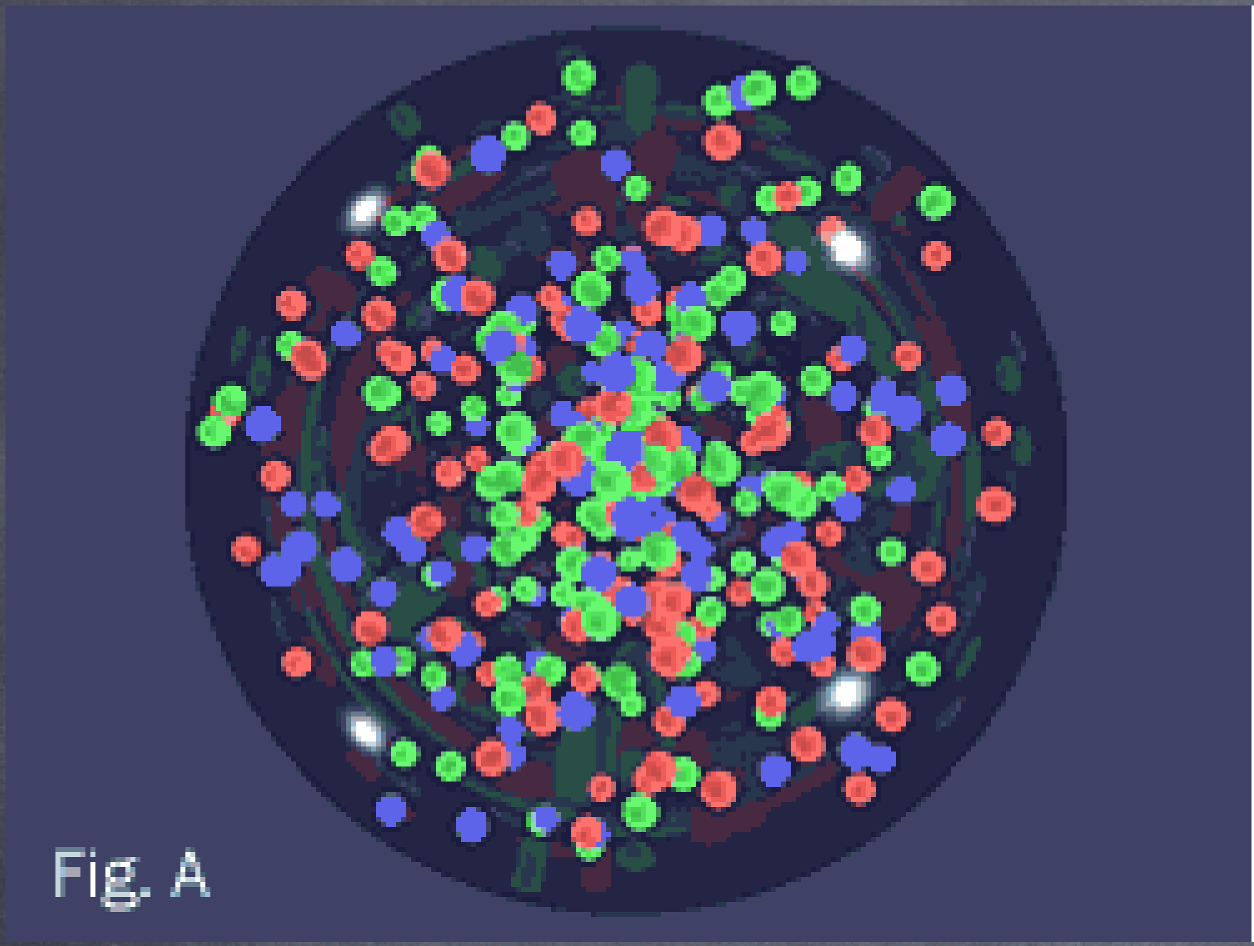


Fig. A

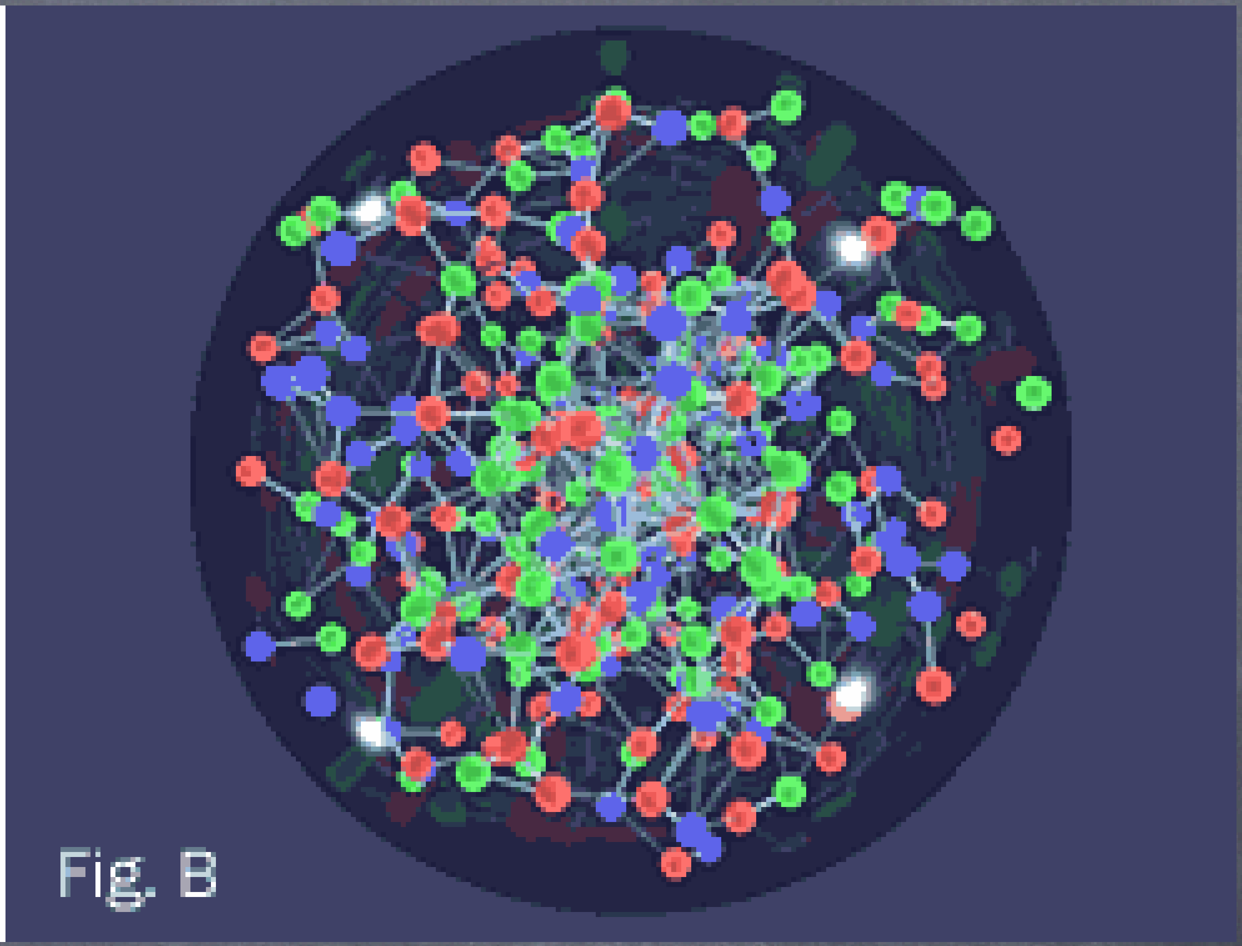


Fig. B

We always hoped that coupling between quarks and gluons would become weak, via "asymptotic freedom" (Nobel Prize in Physics 2004)

But perturbative calculations cannot describe the strong coupling needed for hydrodynamics to be a relevant effective theory for RHIC collisions

Black Holes at RHIC?

Viscosity in Strongly Interacting Quantum Field Theories from Black Hole Physics

P. K. Kovtun,[1] D. T. Son,[2] and A. O. Starinets[3]

[1]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*
[2]*Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*

(Received 20 December 2004; published 22 March 2005)

The ratio of shear viscosity to volume density of entropy can be used to characterize how close a given fluid is to being perfect. Using string theory methods, we show that this ratio is equal to a universal value of $\hbar/4\pi k_B$ for a large class of strongly interacting quantum field theories whose dual description involves black holes in anti–de Sitter space. We provide evidence that this value may serve as a lower bound for a wide class of systems, thus suggesting that black hole horizons are dual to the most ideal fluids.

DOI: 10.1103/PhysRevLett.94.111601 PACS numbers: 11.10.Wx, 04.70.Dy, 11.25.Tq, 47.75.+f

Viscosity Lower Bound

Son et al found that 10-dimensional black holes can be "mapped" onto a strongly-coupled QCD-like "dual" theory, giving a viscosity bound

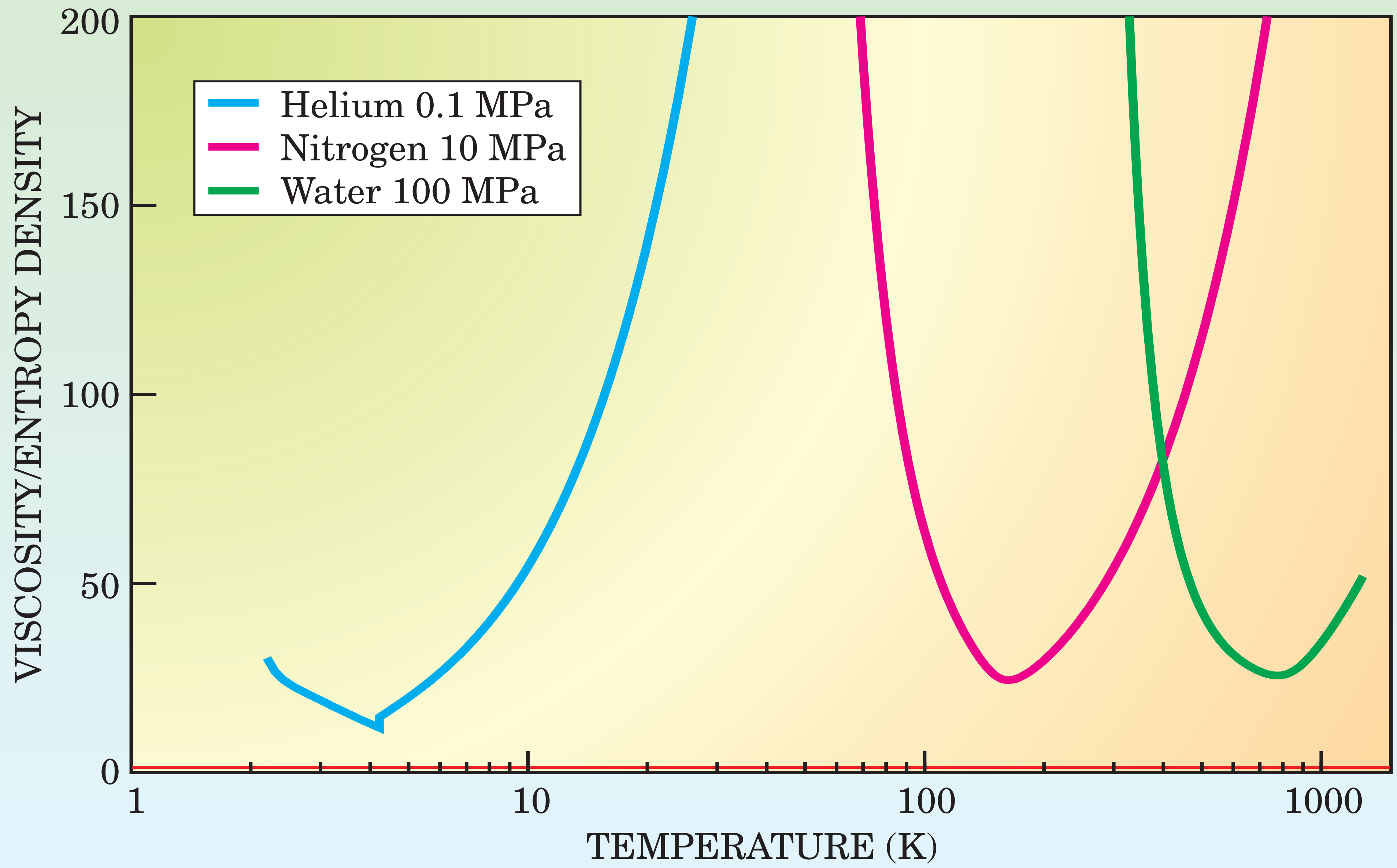
$$\frac{\eta}{s} \geq \frac{1}{4\pi}\frac{\hbar}{k_B}$$

We have already seen that RHIC has a very low viscosity. Does it saturate this bound?

Lower Viscosity Bound

Physics Today, May 2005

P. K. Kovtun, D. T. Son, A. O. Starinets, *Phys. Rev. Lett.* **94** 111601 (2005).



A serious issue for RHIC theory & experiment

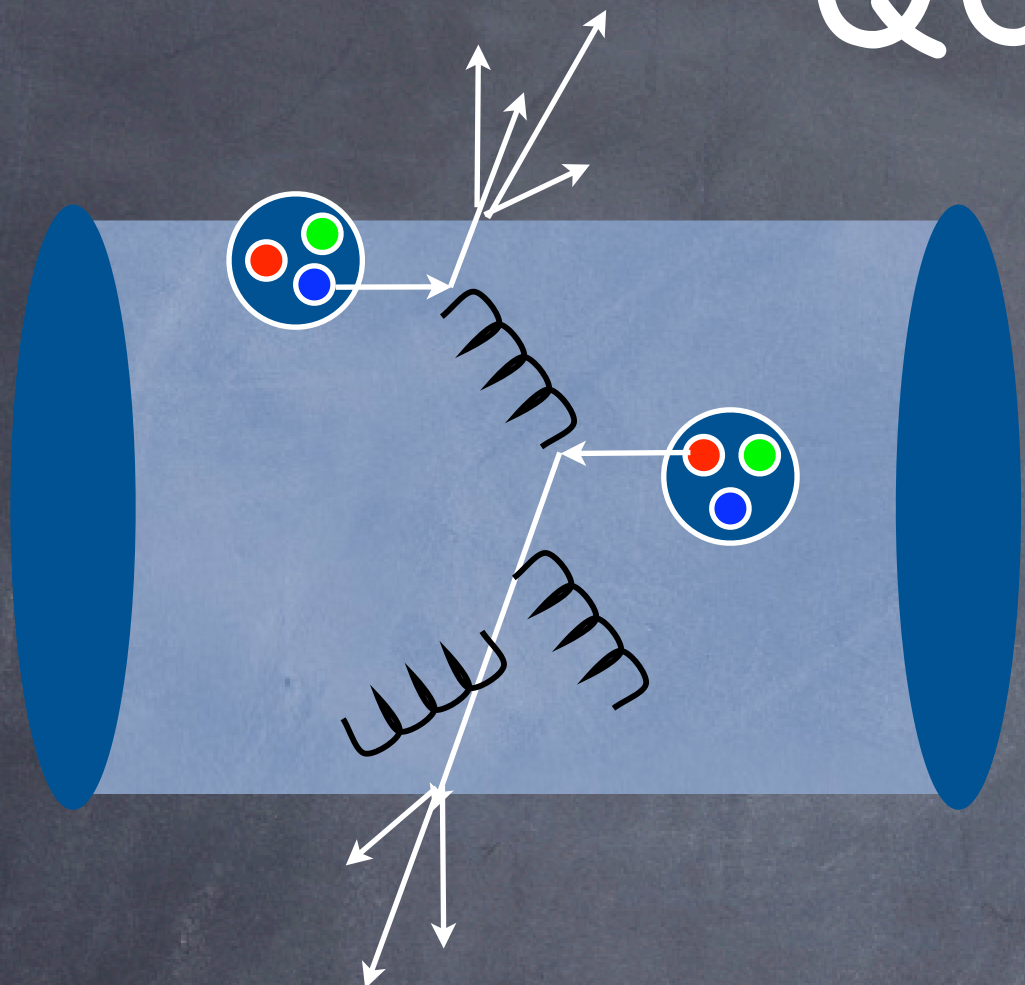
This has been an unconventional discussion of RHIC collisions

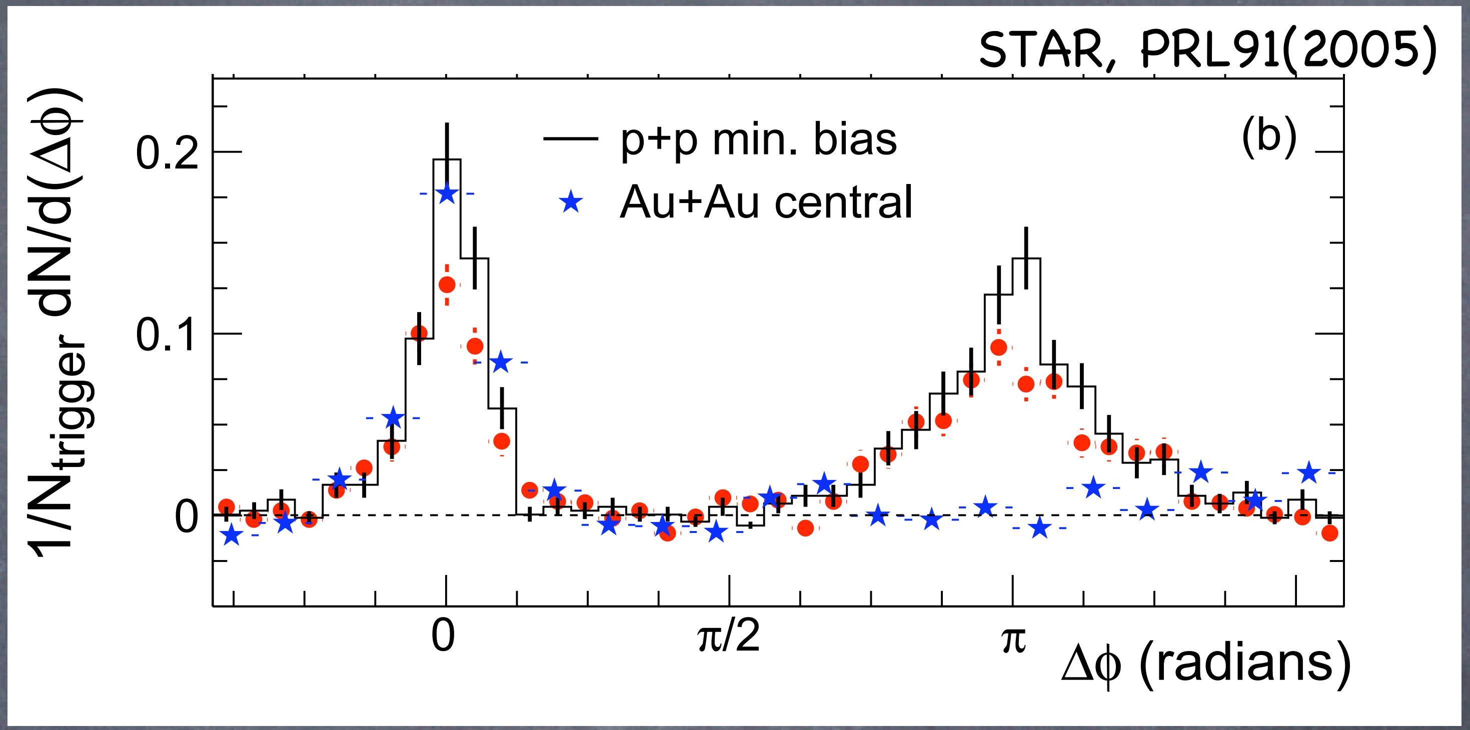
Little discussion of the fundamental theory: QCD

The strongly-coupled nature of the matter gives a primary role to thermochemistry and hydrodynamics

And yet, we must ultimately understand these features via QCD, or perhaps through a dual theory

QCD in A+A





QCD jets from direct scattering between quarks can be "quenched" by the strongly-coupled medium

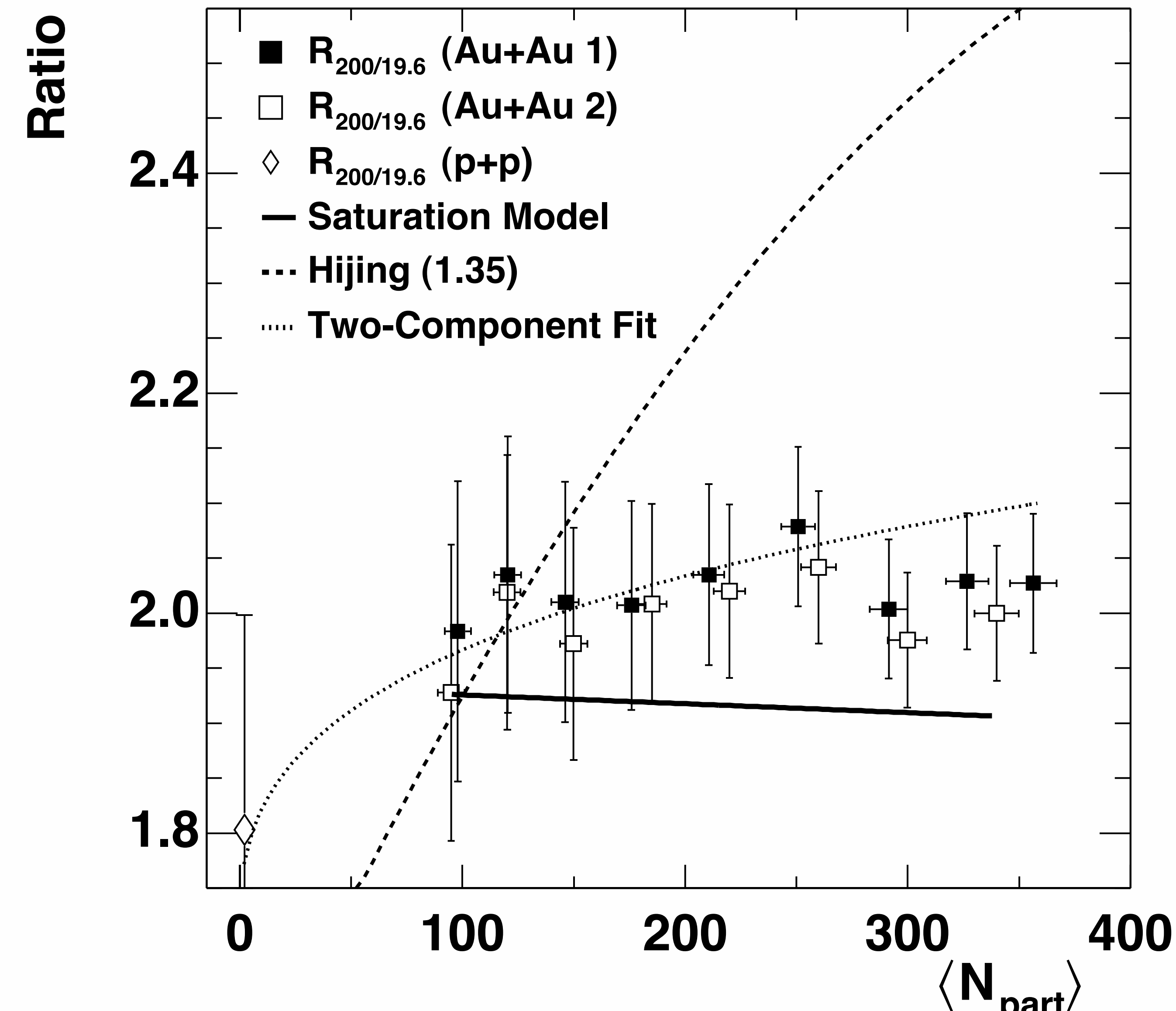
One can study how correlations between particles are reduced by passage through the collision volume

Limits on Hard Processes

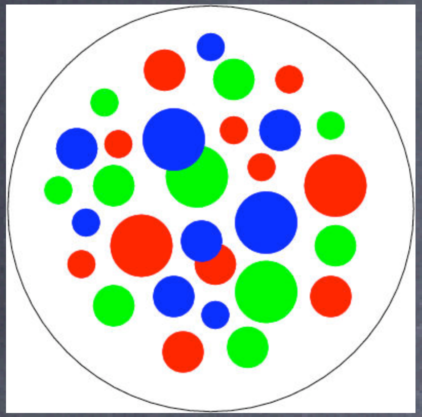
At higher energies, expect particle production at 90 degrees to have more contributions from "hard" QCD processes (scaling as $N_{part}^{4/3}$)

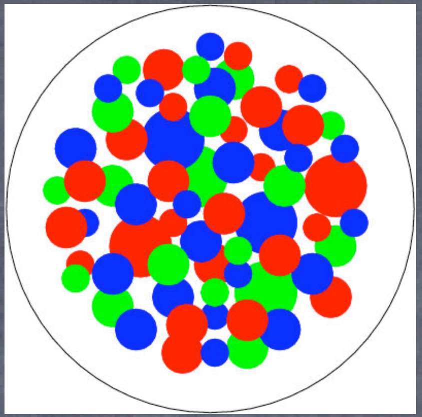
And yet, evolution from peripheral to central events is strangely invariant with beam energy

PHOBOS, PRC70(2004)

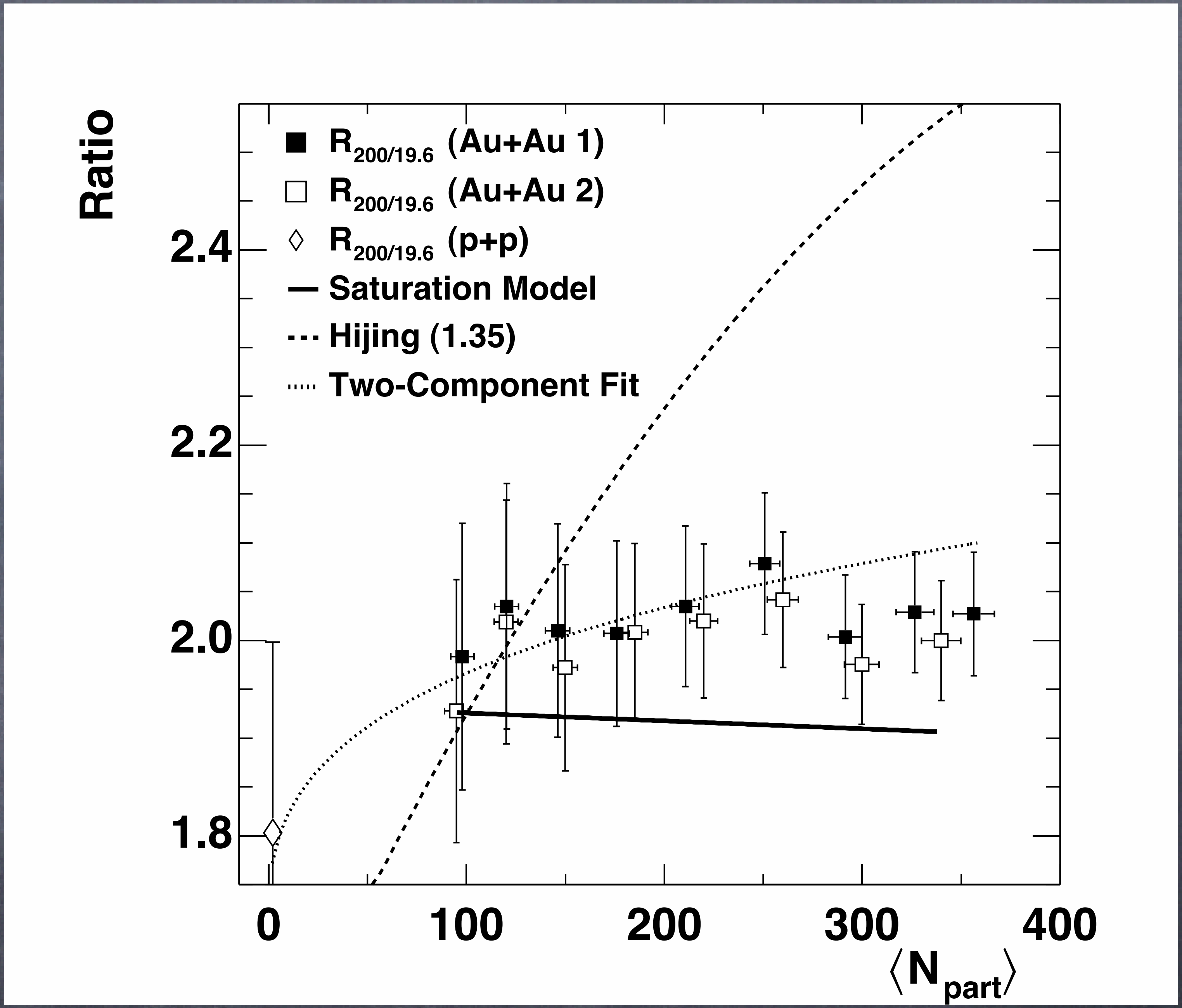


Color Glass Condensate



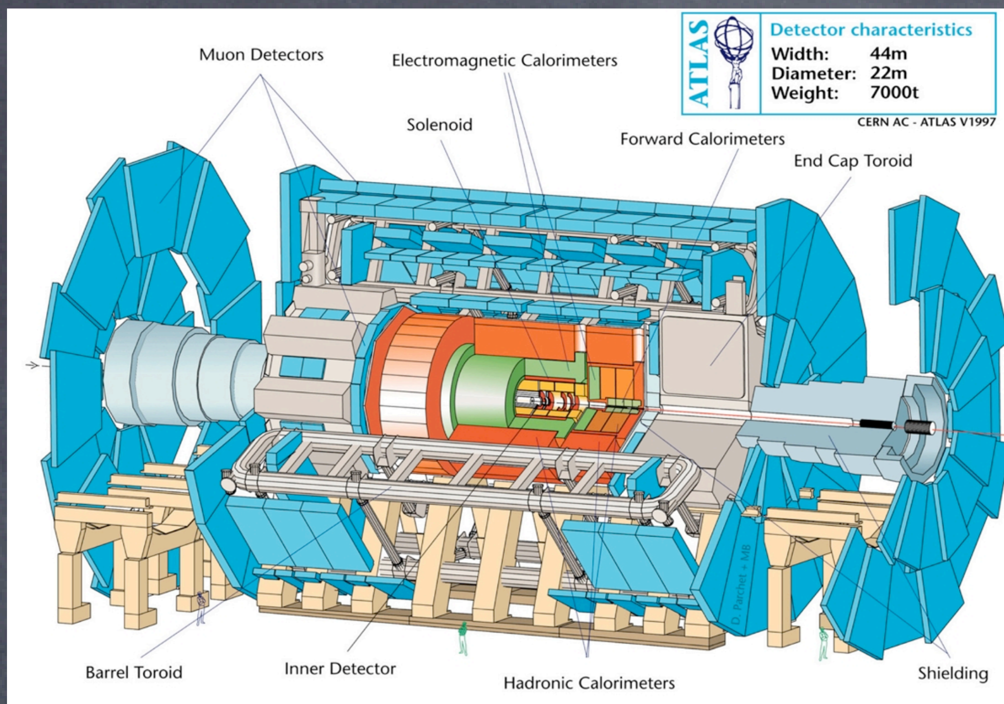


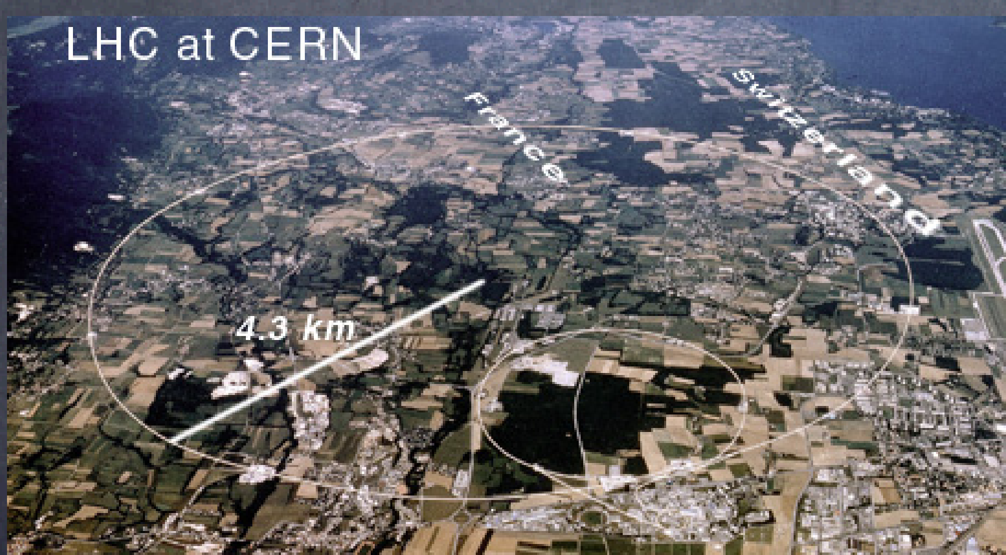
Density of quarks and gluons is so high that hard processes may be effectively suppressed when they fill the available phase space: "parton saturation"

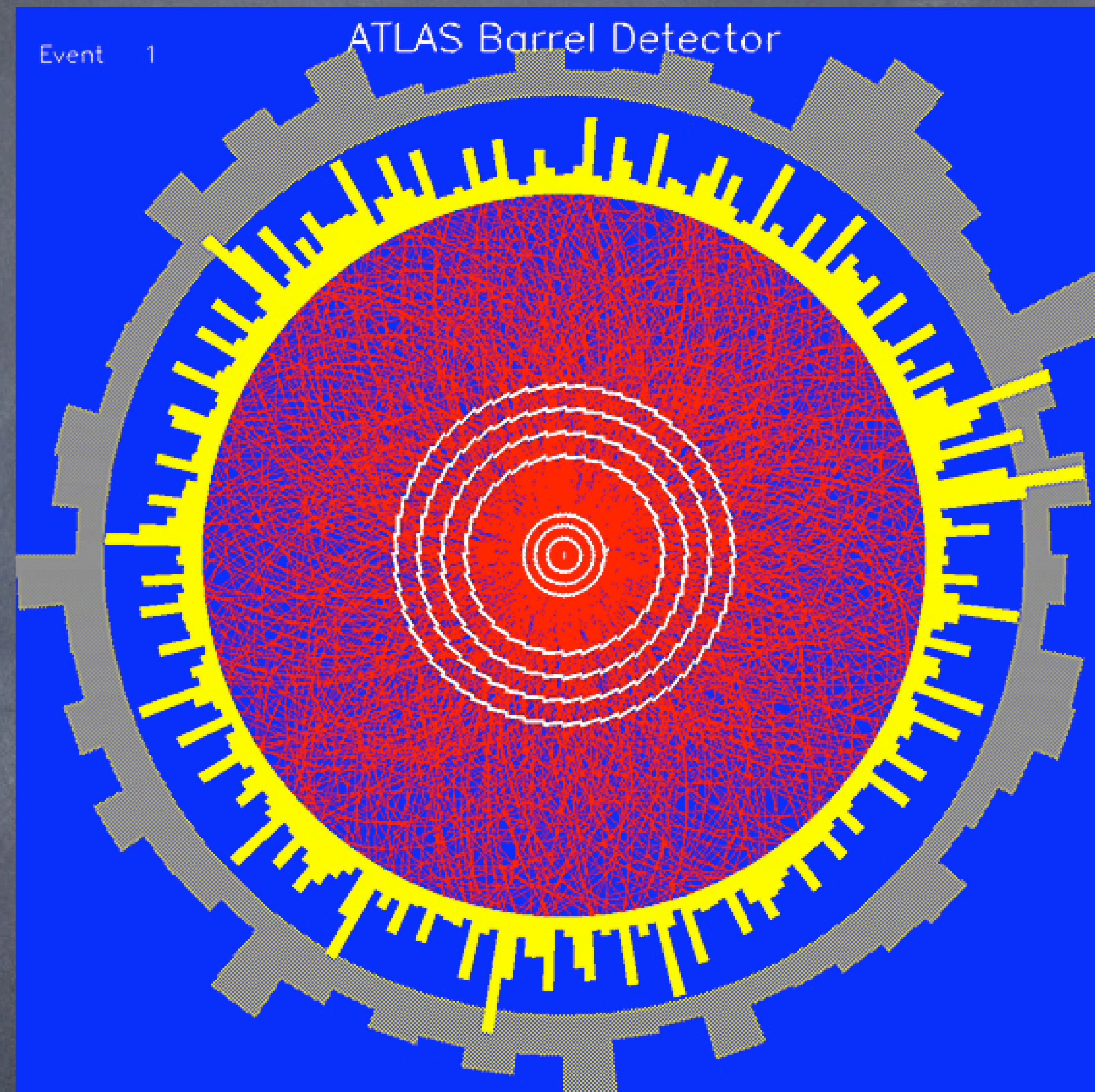


CGC: a new state of matter?

The Future: ATLAS@ALHC

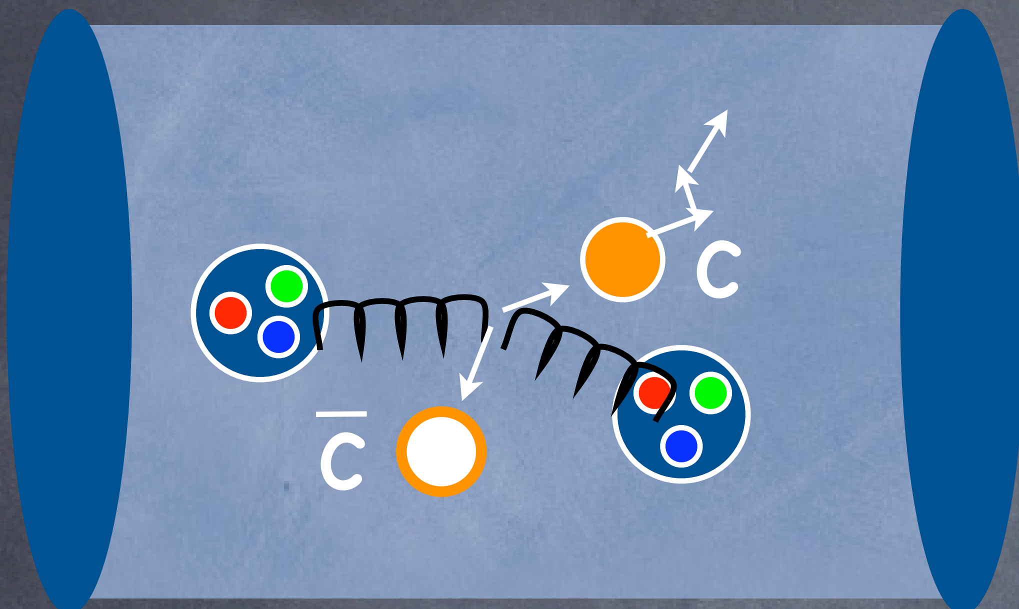


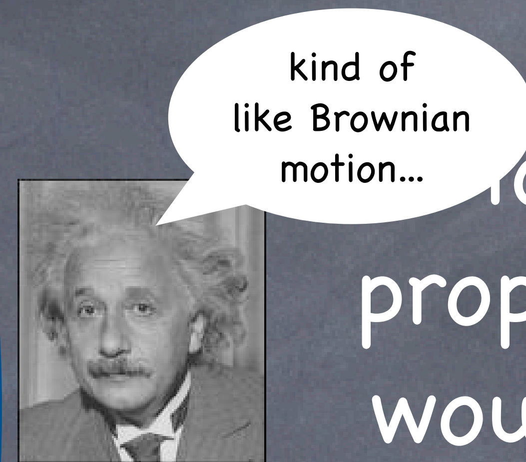




Enormous energies, higher multiplicities:
will the trends discussed here break down?

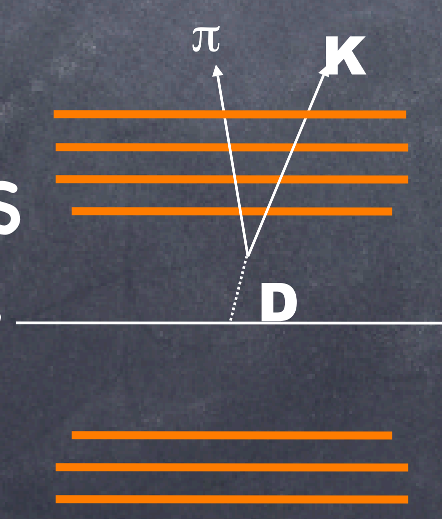
Heavy Flavor @ RHIC II

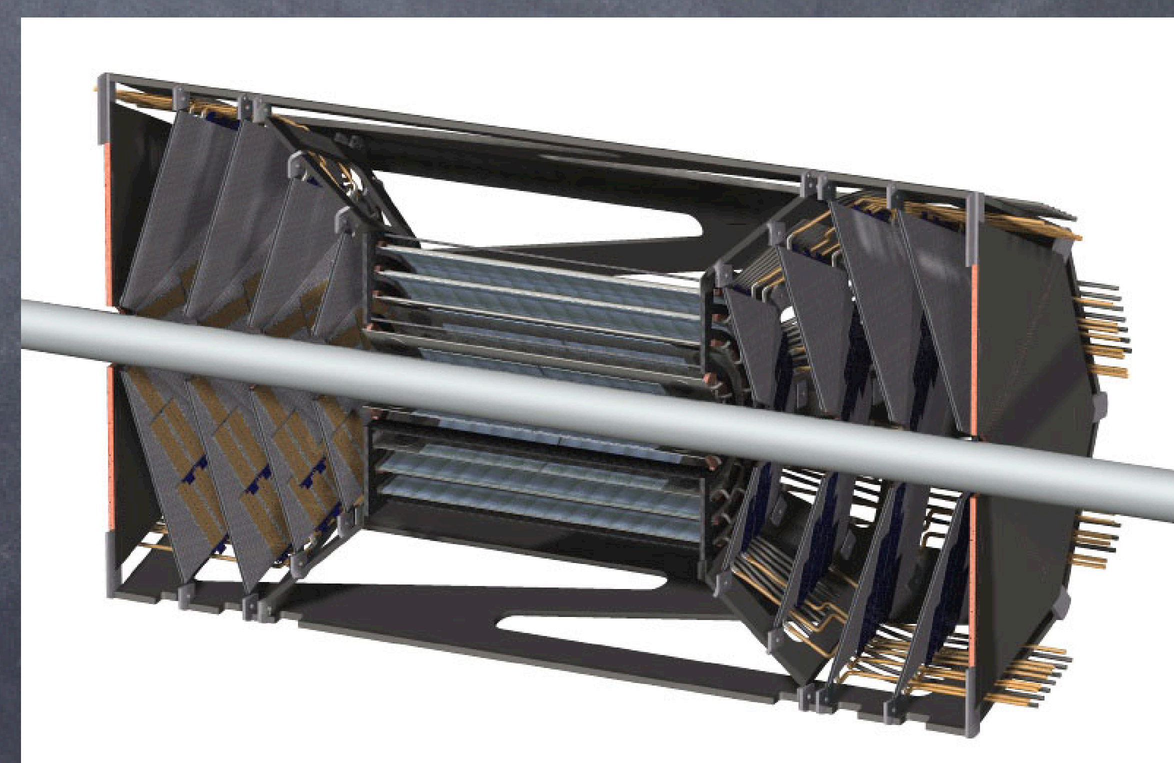




To probe the transport properties of the system, would be useful to study thermalization of heavier objects --> e.g. heavy quarks

New silicon detector being developed for PHENIX to measure charmed particles by means of displaced decay vertices





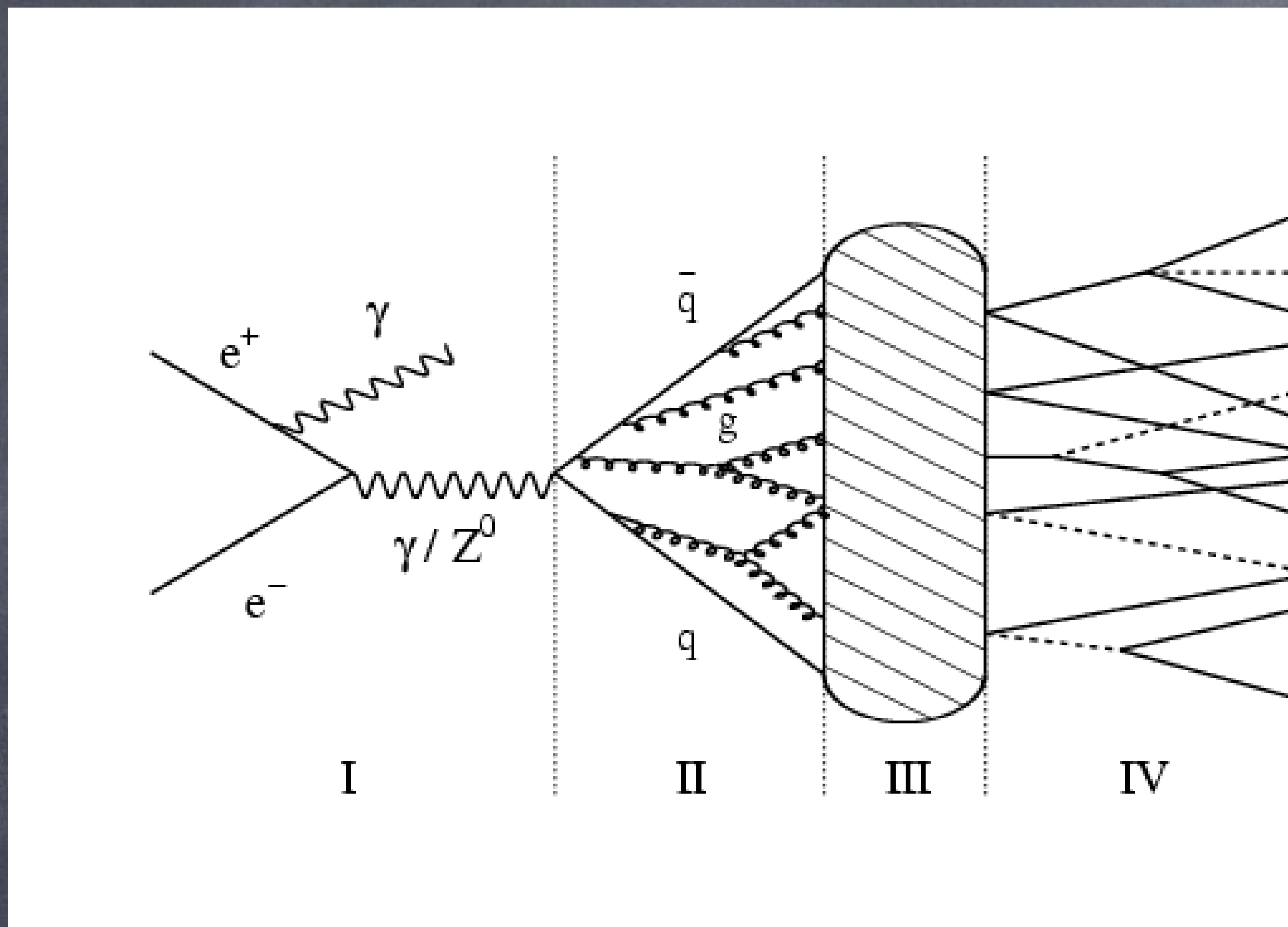

PHOBOS
Birger Back, Mark Baker, Maarten Ballintijn, Donald Barton, Russell Betts, Abigail Bickley,
Richard Bindel, Wit Busza (Spokesperson), Alan Carroll, Zhengwei Chai, Patrick Decowski,
Edmundo Garcia, Tomasz Gburek, Nigel George,
Richard Hollis,
Corey Reed,
Marguerite Belt Tonjes, Adam Trzupek, Carla Vale,
Robin Verdier, Gabor Veres, Edward Wenger, Frank Wolfs, Barbara Wosiek,
Krzysztof Woźniak, Alan Wuosmaa, Bolek Wysłouch, Jinlong Zhang

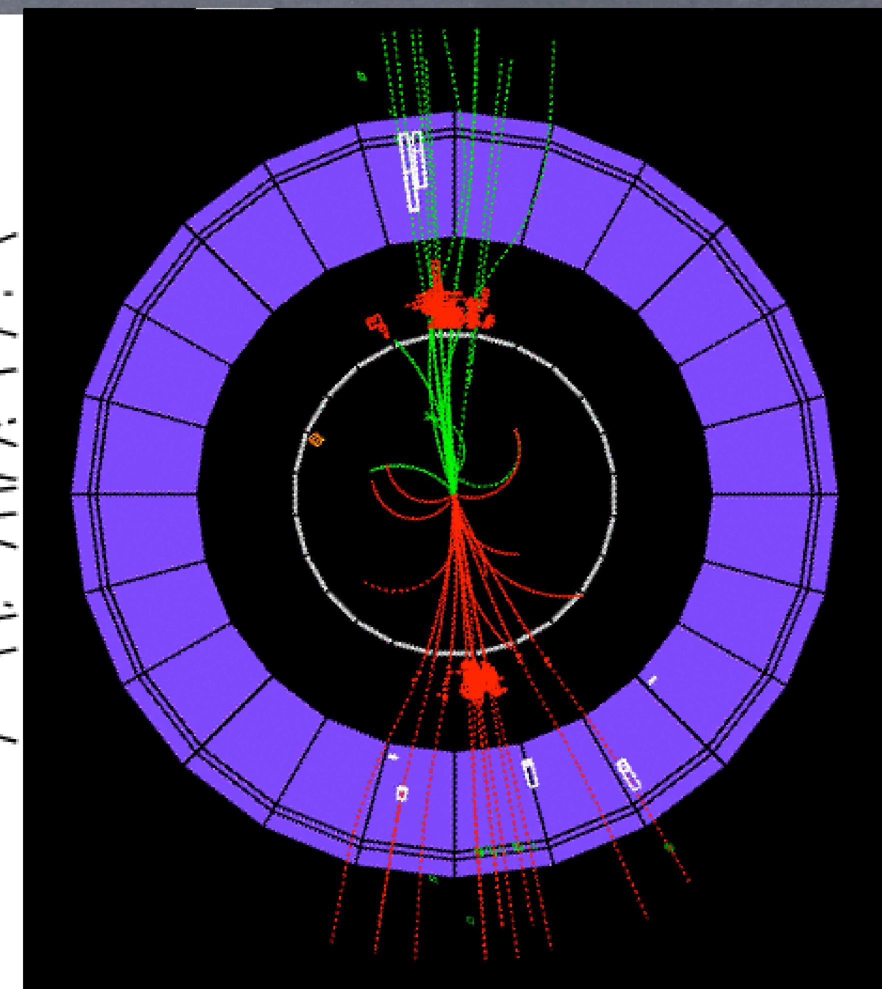
Thanks!

...especially to the BNL Chemistry Department!

Special thanks to Mark Baker, Alex Harris
& Jamie Nagle for discussions related to this talk

QCD in Action





Annihilation into quarks

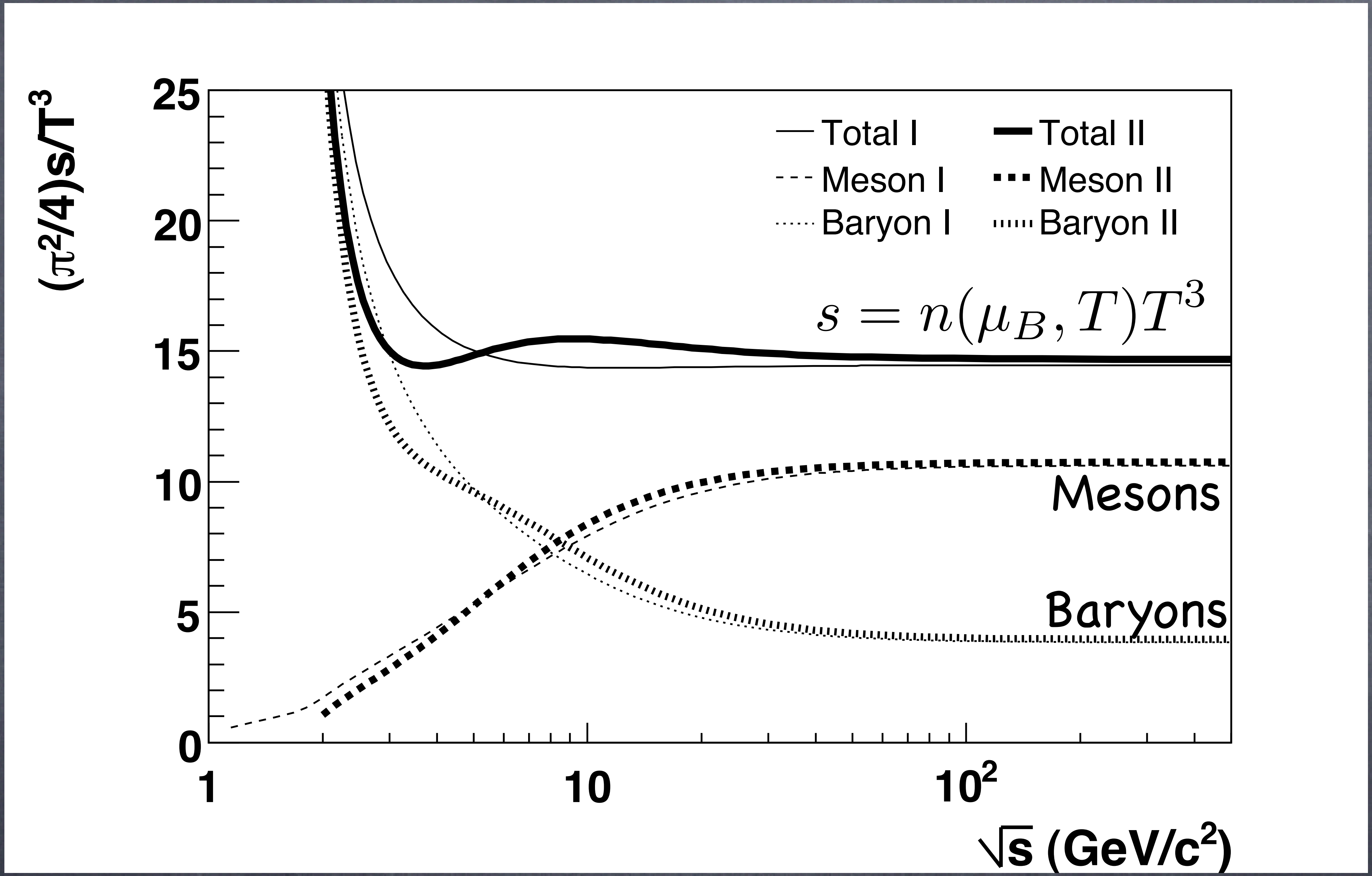
Gluon Radiation

Hadronization & Decays

QCD is a <u>asymptotically-free</u> theory at high energies, with a perturbative description in terms of the radiation of gluons and quarks

--> Jets in e+e- annihilation!

Entropy Density at Freezeout



At the end of the evolution, all systems have similar "number" of degrees of freedom (but very different particles!)

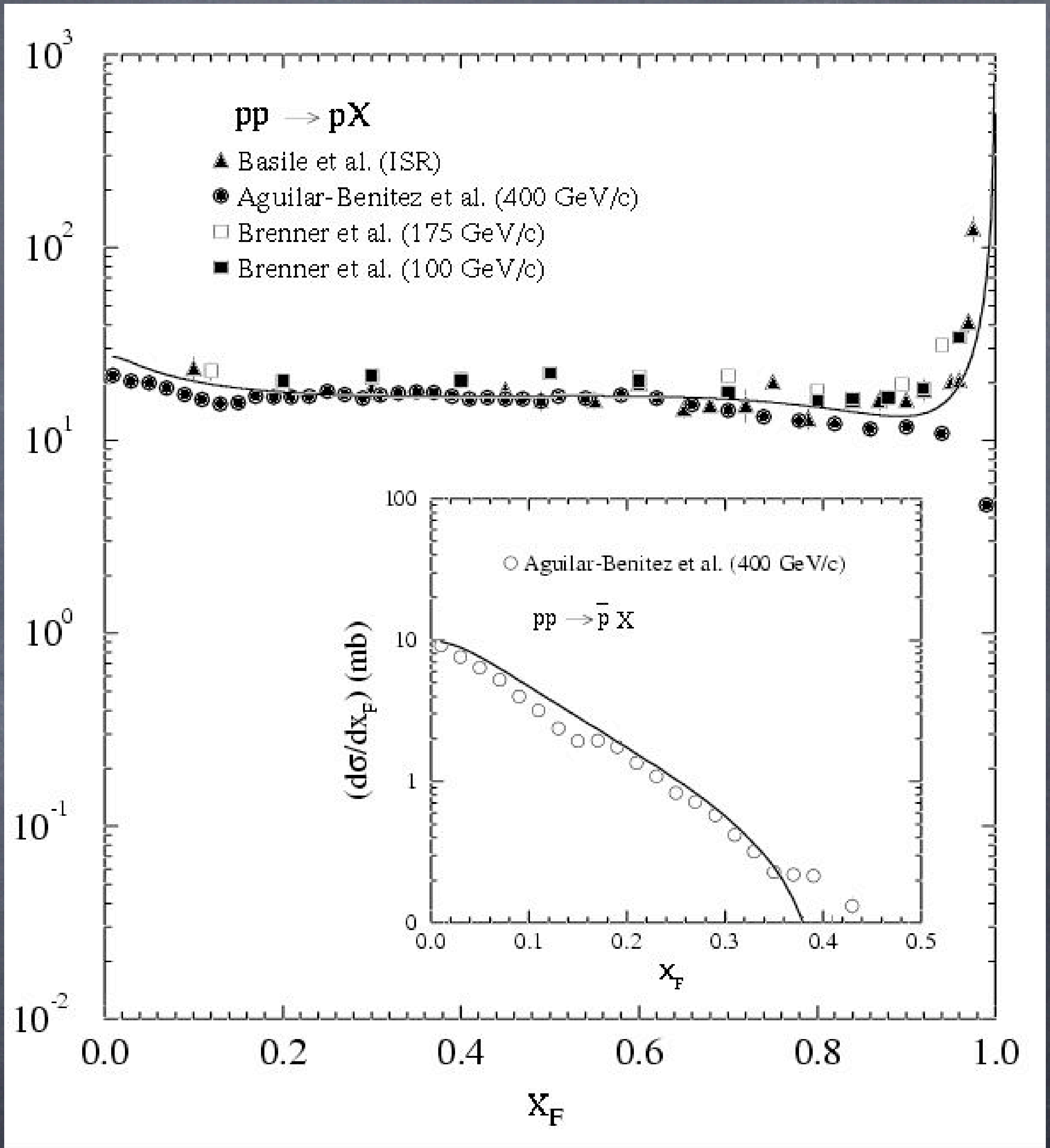
In p+p collisions, there are "leading" particles that can "keep" an arbitrary fraction of the initial energy (which we call "Feynman x", or x_F)

Flat probability distribution:

$$\langle x_F \rangle \sim 1/2$$

$$\sqrt{s_{eff}} = \langle x_F \rangle \sqrt{s} = \frac{\sqrt{s}}{2}$$

"effective energy"



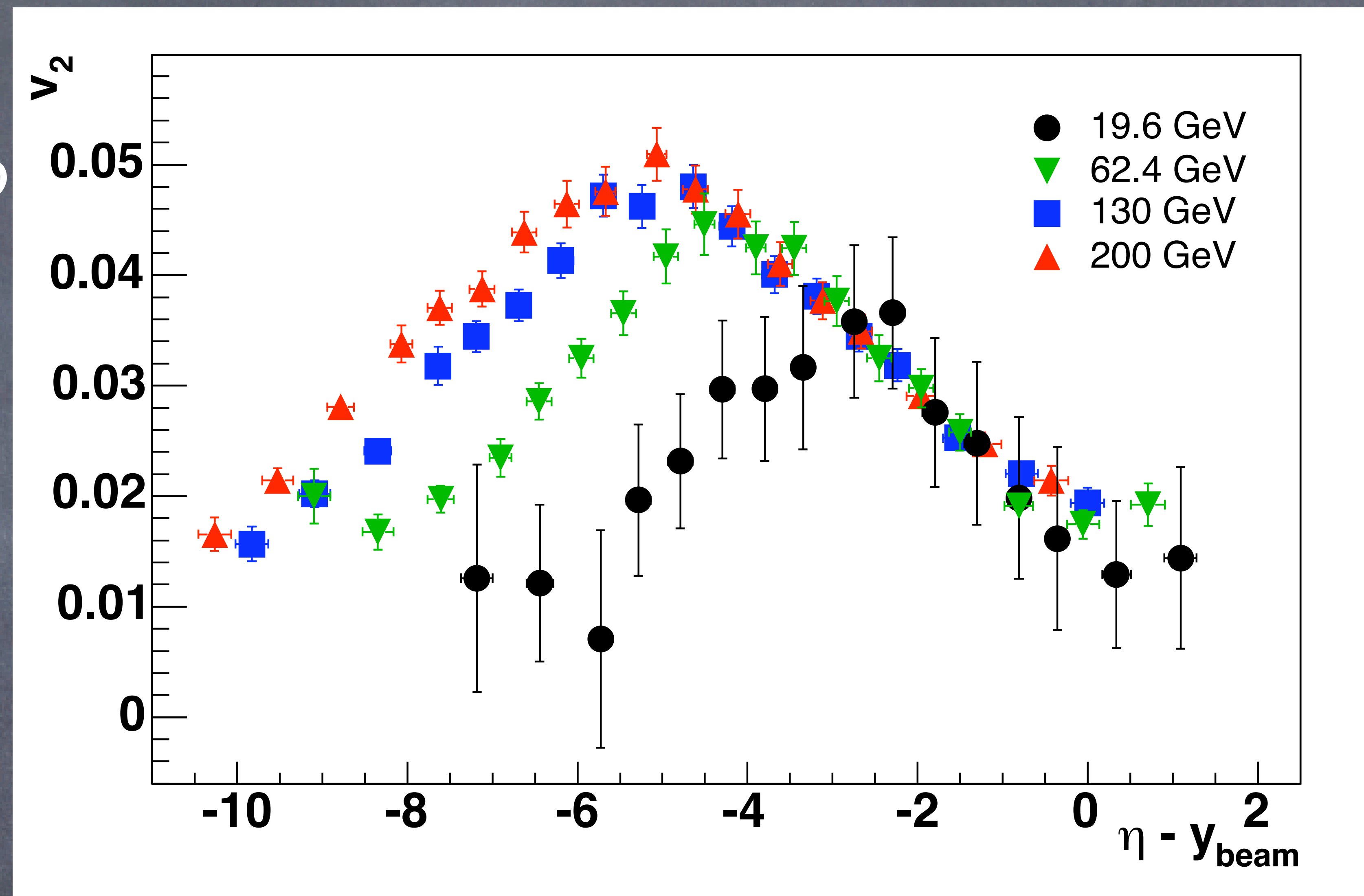
More Longitudinal Scaling?

Just like dN/dη, the asymmetry is also energy-independent viewed from the shifted frame.

So not just $\dfrac{dN}{d\eta'}$,

but $\dfrac{d^2N}{d\eta' d\phi}$,

are energy-independent!



Asymmetry: